Development of a Framework for Sustainable Management of Industrial Food Waste

by

Guillermo Garcia-Garcia

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy

of Loughborough University

Wolfson School of Mechanical, Electrical and Manufacturing Engineering

June 2017

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a degree.

Guillermo Garcia-Garcia

14/06/2017

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisors, Dr. Elliot Woolley and Professor Shahin Rahimifard, for providing constant guidance, advice and support throughout the course of this research, without which the completion of this research and thesis would not have been possible.

I would also like to thank Hana Trollman for helping proofread this thesis. My sincere appreciation also goes to everyone else in the research group for their support and encouragement.

Finally, I dedicate this thesis to my parents Natividad and Enrique, for their love and everything they have taught me in my entire lifetime; and to Julita, who endured this long process with me, always offering invaluable support and endless love.

SYNOPSIS

This thesis reports on the research undertaken to increase the sustainability of the management of industrial food waste. The main objective of this research is to develop a systematic framework that can be used by food manufacturers to identify and implement sustainable solutions for food waste management.

The research reported in this thesis is divided into four main parts. The first part reviews the literature on ramifications and issues associated with the generation and management of food waste, available options to tackle issues related to food waste, categorisations of food waste and existing methodologies to support food waste management modelling and decision-making with regard to the management of food waste. The second part introduces a framework to identify types of food waste and link them to their most sustainable food waste management solution. The third part presents a food waste management modelling procedure and identifies attributes needed to model food waste management. The fourth part analyses relationships between attributes and provides information flowcharts and a methodology to support the modelling of food waste management systems.

The applicability and usefulness of the research have been demonstrated through case studies with two UK food manufacturers: a brewery and a meat-alternative manufacturer. Although the framework presented in this thesis aims at improving food manufacturers' waste management, it could be easily adapted to be used in other stages of the food supply chain.

In summary, the research reported in this thesis has concluded that food manufacturers generate large amounts of food waste that are managed in a wide range of ways. A systematic framework to analyse types of food being wasted, waste management processes, food manufacturers, waste management processors and sustainability implications of food waste management provides a sound methodology to identify opportunities to improve the management of industrial food waste.

ABBREVIATIONS

ABP	Animal By-Product
AD	Anaerobic Digestion
AF	Animal Feeding
AHP/ANP	Analytical Hierarchy Process / Analytic Network Process
ASPID	Analysis and Synthesis of Parameters under Information Deficiency
BOD	Biochemical Oxygen Demand
C	Composting
CBA	Cost-Benefit Analysis
COD	Chemical Oxygen Demand
CPC	Central Product Classification
DEFRA	Department for Environment, Food and Rural Affairs
ELECTRE	ELimination and Choice Expressing REality
FAO	Food and Agriculture Organization of the United Nations
FSC	Food Supply Chain
FUSIONS	Food Use for Social Innovation by Optimising Waste Prevention Strategies
FW	Food Waste
FWH	Food Waste Hierarchy
FWM	Food Waste Management
FWMDT	Food Waste Management Decision Tree
FWMMP	Food Waste Management Modelling Procedure
FWMS	Food Waste Management Solution
GAIA	Geometrical Analysis for Interactive Aid
GHG	Greenhouse gas
GPC	Global Product Category
GSFA	General Standard for Food Additives
HDI	Human Development Index
HRT	Hydraulic Retention Time
IGD	Institute of Grocery Distribution
LATS	Landfill Allowance Trading Scheme
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing

LCSA	Life-Cycle Sustainability Analysis
MAUT	Multi-Attribute Utility Theory
MCDM/MCDA	Multi-Criteria Decision-Making / Multi-Criteria Decision Analysis
MSW	Municipal Solid Waste
NMVOC	Non-Methane Volatile Organic Compounds
OLR	Organic Loading Rate
PAH	Polycyclic Aromatic Hydrocarbons
PCB	PolyChlorinated Biphenyl
PM	Particulate Matter
PROMETHEE	Preference Ranking Organization METhod for Enrichment Evaluations
R	Redistribution
REFRESH	Resource Efficient Food and dRink for the Entire Supply cHain
SDGs	Sustainable Development Goals
SLCA	Social Life-Cycle Assessment
TAN	Total Ammonia Nitrogen
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TRL	Technology Readiness Level
TS	Total Solids
TSS	Total Suspended Solids
TT	Thermal Treatment with energy recovery
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UNEP	United Nations Environment Programme
UNSPSC	United Nations Standard Products and Services Code
VFAs	Volatile Fatty Acids
VIKOR	Multicriteria Optimization and Compromise Solution
VS	Volatile Solids
WRI	World Resources Institute
WRAP	Waste & Resources Action Programme

LIST OF FIGURES

Figure 1-1. Challenges and approaches in the food sector and how to tackle them 2

Figure 1-2. Thesis structure..5

Figure 3-1. Percentage of edible parts of FW (in kcal) in the different regions of the world ..15

Figure 3-2. Percentage of edible parts of FW (based on energy) at different stages for the FSC for different areas of the world (Lipinski et al. 2016)...................................16

Figure 3-3. Split of FW globally (edible parts only) by types of food (Lipinski et al. 2013).....16

Figure 3-4. Percentage of FW in different stages of the FSC in Europe. Adapted from FUSIONS (2016)..18

Figure 3-5. FW in European countries per capita (kg per year) (European Commission (DG ENV) 2010) 19

Figure 3-6. Percentage of FW in the manufacturing sector / food produced (European Commission (DG ENV) 2010)..19

Figure 3-7. Quantity of FW generated in the different stages of the UK FSC, in Mt 21

Figure 4-1. Food waste management solutions (FWMSs), arranged in the food waste hierarchy (FWH)..39

Figure 4-2. Use of different FWMSs across the UK FSC, in kt..54

Figure 5-1. Proportions of avoidable FW in households in 2012 by weight and cost. Adapted from Quested et al. (WRAP) (2013) ®WRAP..59

Figure 6-1. Stages to decide different types of research. Based on Kothari (2004) 77

Figure 6-2. Technology Readiness Levels. Based on EARTO (2014) 79

Figure 6-3. Research methodology 84

Figure 7-1. Structure of the research approach proposed...86

Figure 7-2. Definitions of 'food wastage', 'food losses' and 'food waste', according to FAO (2011) and Lipinski et al. (2013). Definitions from (Think.Eat.Save 2014)..........87

Figure 7-3. Different aspects included in the definition of 'food waste' according to FAO (2011), Lipinski et al. (WRI) (2013), Quested & Johnson (WRAP) and (2009 FUSIONS (2014) 89

Figure 7-4. Types of food material at different phases of a food manufacturing site 96

Figure 7-5. Qualitative parameters to categorise FW and the nine-stage FW categorisation97

Figure 7-6. Waste hierarchy for surplus food and FW 102

Figure 7-7. The Food Waste Management Decision Tree. Edible, eatable, animal-based FWs and their most sustainable FWMSs 109

Figure 7-8. The Food Waste Management Decision Tree. Edible, eatable, plant-based FWs and their most sustainable FWMSs 110

Figure 7-9. The Food Waste Management Decision Tree. Edible, uneatable FWs and their most sustainable FWMSs 111

Figure 7-10. The Food Waste Management Decision Tree. Inedible and uneatable for humans, eatable for animals FWs and their most sustainable FWMSs 112

Figure 8-1. Stages of the Food Waste Management Modelling Procedure 115

Figure 8-2. Major phases in the operation of the FWMMP 116

Figure 9-1. Integration of tools to obtain information flow diagrams 138

Figure 9-2. Example 1: 24x7 matrix showing an analysis of 168 relationships between some quantitative primary FW parameters and environmental impact to air indicators. A green tick denotes presence of relationship and a red cross absence of relationship 140

Figure 9-3. Example 2: 29x7 matrix showing an analysis of 203 relationships between performance factors and FW parameters 141

Figure 9-4. 24x7 matrix showing an analysis of 168 relationships between some secondary quantitative FW parameters and environmental impact to air indicators 144

Figure 9-5. 11x7 matrix showing an analysis of 77 relationships between some secondary quantitative FW parameters and environmental impact to air indicators. Indicators with same relationships have been grouped 145

Figure 9-6. 10x7 matrix showing an analysis of 70 relationships between some performance factors and environmental indicators 146

Figure 9-7. Section of the Dependencies List for redistribution for human consumption showing dependencies to five attributes 146

Figure 9-8. Information flowchart for redistribution for human consumption 149

Figure 9-9. Information flowchart for animal feeding 150

Figure 9-10. Information flowchart for anaerobic digestion 151

Figure 9-11. Information flowchart for composting 152

Figure 9-12. Information flowchart for thermal treatment with energy recovery 153

Figure 9-13. Methodology used to build the 'List of attributes needed' in the Table of Assessment 155

Figure 9-14. Information flow diagram built from Table 9-4. Green attributes: known attributes, red attributes: unknown attributes, attributes in yellow R boxes: required attributes 159

Figure 10-1. Information flow diagram for waste beer 174

Figure 10-2. Information flow diagram for filter waste 178

Figure 10-3. Information flow diagram for food product returns 187

LIST OF TABLES

Table 3-1. Causes of generation of avoidable FW in the production stage 30

Table 3-2. Causes of generation of avoidable FW in the manufacturing stage 30

Table 3-3. Causes of generation of avoidable FW during distribution 31

Table 3-4. Causes of generation of avoidable FW in the retail stage 31

Table 3-5. Causes of generation of avoidable FW in the food service stage 31

Table 3-6. Causes of generation of avoidable FW in the household stage 32

Table 4-1. Examples of FW types that cannot be managed following some FWMSs 52

Table 5-1. Most relevant LCA software tools and examples of their use to model waste management 65

Table 7-1. Situations in the food systems when a material becomes food, and when food becomes waste 93

Table 8-1. Qualitative FW parameters 119

Table 8-2. Quantitative primary FW parameters..120

Table 8-3. Quantitative secondary FW parameters 122

Table 8-4. FWM process and company status variables 124

Table 8-5. FWM performance factors...126

Table 8-6. Environmental indicators: impacts to air 129

Table 8-7. Environmental indicators: impacts to water 130

Table 8-8. Environmental indicators: impacts to soil...132

Table 8-9. Economic indicators 134

Table 8-10. Social indicators 135

Table 9-1. Discarded dependencies from the Relationships Matrix 148

Table 9-2. An example of a section of the Table of Assessment for Redistribution for human consumption 154

Table 9-3. An example of a section of the Table of Assessment for Redistribution for human consumption in which the user has determined which values are known (Y), which are unknown (N) and which are required (R) 157

Table 9-4. Results Table of the example presented in Table 9-3 158

Table 10-1. Categorisation of spent grain and identification of its most sustainable FWMS 164

Table 10-2. Categorisation of waste beer and identification of its most sustainable FWMS 166

Table 10-3. Categorisation of conditioning bottom and identification of its most sustainable FWMS 168

Table 10-4. Categorisation of filter waste and identification of its most sustainable FWMS 169

Table 10-5. Categorisation of trub waste and identification of its most sustainable FWMS 170

Table 10-6. Table of Assessment for waste beer 171

Table 10-7. Results Table for waste beer 173

Table 10-8. Section of Table of Assessment for filter waste showing categories of attributes, attributes to asses, known/unknown attributes, and required attributes 175

Table 10-9. Results Table for filter waste 177

Table 10-10. Categorisation of the food solid/slurry mix and identification of its most sustainable FWMS 182

Table 10-11. Categorisation of food product returns and identification of its most sustainable FWMS 183

Table 10-12. Table of Assessment for food product returns 185

Table 10-13. Results Table for food product returns 186

TABLE OF CONTENTS

Acknowledgements .... **III**

Synopsis .... **IV**

Abbreviations .... **V**

List of figures .... **VII**

List of tables .... **X**

Table of contents .... **XII**

CHAPTER 1 Introduction **1**

CHAPTER 2 Research justification and scope **6**

2.1 Introduction 6

2.2 Research context 6

2.3 Research questions 8

2.4 Research aim and objectives 8

2.5 Research scope 9

2.6 Chapter summary 11

CHAPTER 3 A review of issues associated with the generation and management of food waste **12**

3.1 Introduction 12

3.2 Overview of food security 12

3.3 Quantification of food waste 13

3.3.1 Global food waste *14*

3.3.2 Food waste in Europe *16*

3.3.3 Food waste in the UK *20*

3.4 Assessment of impacts related to the food waste issue 25

3.4.1 Global impacts *25*

3.4.2 Impacts in Europe *27*

3.4.3 Impacts in the UK 28

3.5 Evaluation of the causes behind the generation of food waste in the FSC 29

3.6 Chapter summary 32

CHAPTER 4 A review of options to tackle issues related to food waste 34

4.1 Introduction 34

4.2 Initiatives to tackle food waste 34

4.2.1 Global initiatives 34

4.2.2 European initiatives 35

4.2.3 Initiatives in the UK 36

4.3 Food waste management solutions: the food waste hierarchy 38

4.3.1 Introduction and legislative framework 38

4.3.2 Reduction 40

4.3.3 Reuse 41

4.3.4 Recycling 43

4.3.5 Recovery 47

4.3.6 Disposal 50

4.3.7 Applicability of the food waste hierarchy 52

4.4 Quantification of food waste management solutions in the UK food supply chain .. 53

4.5 Chapter summary 55

CHAPTER 5 A review of categorisations and methodologies for food waste management 57

5.1 Introduction 57

5.2 Categorisations of food waste 57

5.2.1 European regulations 58

5.2.2 Categorisations of FW by food type 58

5.2.3 Categorisations of FW based on other criteria 60

5.3 Methodologies and tools to support food waste management 62

5.3.1 Life-cycle assessment 63

5.3.2 Cost–benefit analysis 66

5.3.3 Multi-criteria decision-making / multi-criteria decision analysis 67

5.3.4 Other methodologies...72

5.3.5 Applicability of existing methodologies to support food waste management ...74

5.4 Chapter summary..75

CHAPTER 6 Research methodology 77

6.1 Introduction...77

6.2 Overview of research types 77

6.3 Research methodology 79

6.3.1 Type of research used in this thesis...79

6.3.2 Phases of the research methodology 82

6.4 Chapter summary..83

CHAPTER 7 A framework for identification of food waste types and their most sustainable waste management solution.. 85

7.1 Introduction...85

7.2 Definitions of food waste and the food system...87

7.2.1 Definition of food waste 87

7.2.2 Determination of the boundaries of food systems..92

7.3 Identification of types of food waste..94

7.4 Qualitative parameters to classify food waste 95

7.4.1 Edibility 98

7.4.2 State..98

7.4.3 Origin...98

7.4.4 Complexity 99

7.4.5 Animal-material presence...99

7.4.6 Treatment..99

7.4.7 Packaging 99

7.4.8 Packaging biodegradability..100

7.4.9 Stage of the supply chain 100

7.4.10 Applicability of the FW categorisation 100

7.5 A methodology to find the most sustainable waste management solution for each type of food waste 100

7.5.1 Selection of the version of the FWH to classify FWMSs................................101

7.5.2 The Food Waste Management Decision Tree 108

7.6 Chapter summary..113

CHAPTER 8 Quantitative attributes to model food waste management 114

8.1 Introduction..114

8.2 Overview of the Food Waste Management Modelling Procedure 114

8.3 Stages of the Food Waste Management Modelling Procedure 118

8.3.1 Parameters to define characteristics of FW 119

8.3.2 Variables to model FWM processes and company status...............................123

8.3.3 Factors to assess the performance of FWM practices...................................125

8.3.4 Sustainability indicators to evaluate ramifications of FWMSs.........................127

8.4 Chapter summary..136

CHAPTER 9 Analysis of information flows for food waste management................................138

9.1 Introduction..138

9.2 Relationships between attributes: building the Relationships Matrix 138

9.2.1 Combination of attributes...144

9.2.2 Streamlined Relationships Matrix..145

9.2.3 Dependencies List 146

9.3 Information flowcharts to model FWMSs...148

9.4 Methodology to assess information flows..154

9.4.1 Building the Table of Assessment..154

9.4.2 Using the Table of Assessment to obtain the Results Table and information flow diagrams..156

9.5 Chapter summary..160

CHAPTER 10 Case studies..161

10.1 Introduction..161

10.2 Brewery: Molson Coors 162

10.2.1 Identification and categorisation of FWs, and selection of a FWMS 163

10.2.2 Analysis of information flows 171

10.2.3 Discussion and conclusions of the research applied to Molson Coors 176

10.3 Manufacturer of meat alternatives: Quorn Foods 180

10.3.1 Identification and categorisation of FWs, and selection of a FWMS 180

10.3.2 Analysis of information flows 184

10.3.3 Discussion and conclusions of the research applied to Quorn Foods 187

10.4 Chapter summary 189

CHAPTER 11 Concluding discussions 190

11.1 Introduction 190

11.2 Research contributions 190

11.3 Concluding discussion 191

CHAPTER 12 Conclusions and further work 199

12.1 Introduction 199

12.2 Research conclusions 199

12.3 Further work 201

References 206

Appendices A1

Appendix 1: Food waste questionnaire A2

Appendix 2: Journal paper A4

Appendix 3: Conference paper A5

Appendix 4: Conference paper A12

Appendix 5: Journal paper A19

Appendix 6: Journal paper A34

Appendix 7: Conference paper A54

Appendix 8: Book chapter A63

CHAPTER 1 INTRODUCTION

The food industry is one of the largest and most important industrial sectors. Everybody, except subsistence farmers and hunter-gatherers, rely on the food industry to feed themselves and their families every day. The food industry is formed of very diverse members, from multi-national manufacturers that process and package food, to sole traders that sell food in markets.

The food industry is significantly affected by a number of issues and challenges that humanity is currently facing, covering a broad range of different disciplines, including aspects as diverse as those from environmental, social, economic, political and demographical spheres. Some of the most important issues having a very significant influence on global food systems worldwide are:

- Climate change and pollution of air, water and soil, which impact the ability to grow crops (e.g. droughts).
- The rapidly growing population: global population is estimated to reach 9.6 billion by 2050 (United Nations 2013). A fast-growing population affects the ability to feed the entire human population.
- New trends in consumerism, which includes over-consumption, use of more processed foods and demand for healthier products, principally in developed regions. In late-stage developing countries which are developing rapidly a high consumption of meat also creates significant challenges; for instance, meat consumption is expected to rise by 46% in China and 94% in India, the two most populated countries in the world, between 2006 and 2050 (World Resources Institute 2013).

In the 20th century the most common approach to feeding the rapidly growing global population was to increase total food production, which was achievable principally because of the use of more efficient and effective fertilizers and pesticides and the development of new technologies and varieties of food (FAO n.d.). An alternative approach to increasing food availability, especially useful for low-income societies, is to reduce current levels of food waste (FW) and redirect surplus food to people in need. It is estimated that preventing and redirecting just 25% of global FW would be sufficient to eliminate human starvation globally (Save Food n.d.).

Figure 1-1 summarises the most important challenges in the food sector and possible approaches to tackle them, according to the author's opinion and knowledge. The most relevant links amongst challenges and between approaches and challenges are represented with arrows. It can be seen that an increase in food production only tackles the growing food demand issue, but increasing the efficiency of food systems tackles the most important challenges in the food sector.

Increasing the efficiency of food systems can only be achieved through a reduction of the waste generated. Currently, food systems are extremely inefficient due to their high FW generation rate. It is estimated that between one-third and one-half of the food produced for human consumption is wasted (FAO 2011, Institute of Mechanical Engineers 2013). The Sustainable Development Goal 12 "Ensure sustainable consumption and production patterns" established by the United Nations in 2015 includes a specific target for FW reduction: halve per capita global FW at retail and consumer levels by 2030. Additionally, it also includes a more general goal to reduce food loss across food supply chains (FSCs) (United Nations 2015). In the European Union, an EU Platform on Food Losses and Food Waste has been created (European Commission. Directorate-General for Health and Food Safety 2016) following the call on the European Commission by the Communication on Circular Economy (European Commision 2015). The EU has also recently funded the following projects with the aim of finding solutions to the FW issue: FoRWaRD (European Commission n.d.), FUSIONS (European Commission Framework Programme 7 n.d.) and REFRESH (Horizon 2020 Framework Programme of the European Union n.d.). In summary, it is expected that there will be an increasing number of legislative developments, initiatives and campaigns to tackle FW.

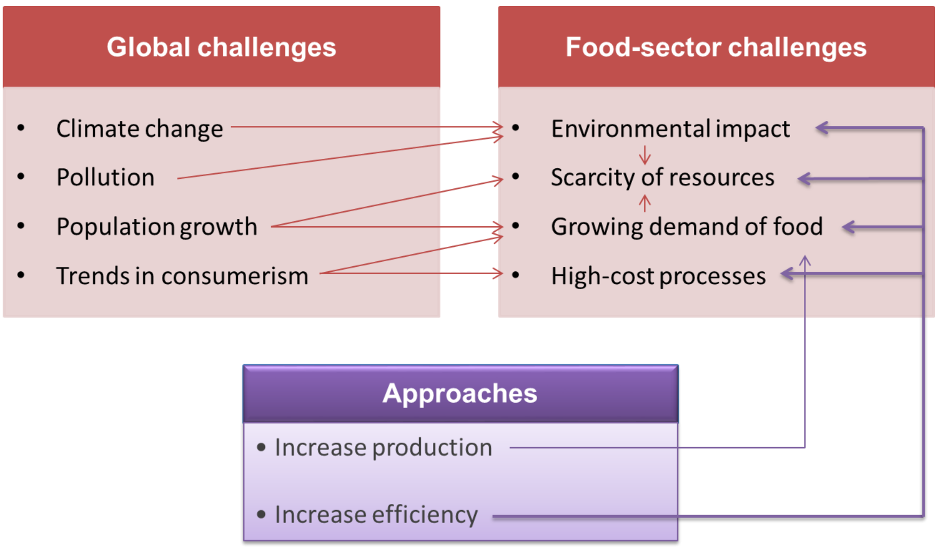


Figure 1-1. Challenges and approaches in the food sector and how to tackle them

Nevertheless, it is unrealistic to completely remove FW from FSCs: inevitably some FW will always be generated due to a number of reasons, such as overproduction, damages to the food during manufacturing, human errors; and also because most raw materials in the food sector have inedible associated materials, i.e. food by-products. Therefore, reduction of the current FW volumes must be accompanied by better management of the FW that remains. There are countless possibilities to manage FW, yet the most common solution worldwide is landfilling (FAO 2013b), which heavily damages both the environment and human health, providing only little benefit. In spite of the progress achieved in recent years to find alternative solutions, particularly in developed nations, an improved management of FW in FSCs is still needed.

Consequently, sustainable management of FW is a vibrant research area that has grown rapidly over recent years (Chen et al. 2017). This research area aims to find more sustainable ways to manage FW, i.e. to reduce environmental, economic and social impacts whilst maximising potential benefits. There are several meritorious examples of research aiming to find sustainable solutions for food waste management (FWM), but they have been generally inclined to look into only one domain of sustainability: environmental, economic or social ramifications (Griffin et al. 2009, Thyberg & Tonjes 2015). Recent research aims to expand the scope and consider two or even all three pillars of the aforementioned sustainability ramifications. Notable examples are work by Münster et al. (2015), Ahamed et al. (2016) and Martinez-Sanchez et al. (2016), who consider economic and environmental ramifications of FWM.

In Europe, it has been estimated that the percentage of total FW generated at the manufacturing stage of FSCs is between 39% for EU-27 (European Commission (DG ENV) 2010) and 19% for EU-28 (FUSIONS 2016); this difference can be partially explained because the latter estimation does not include FW diverted to animal feeding or biochemical processing. In the UK, food manufacturers generate about 5.2 million tonnes (Mt) of FW per year, including redistributed food, FW diverted to animal feeding and food by-products (Parfitt, Woodham, et al. 2016), out of approximately 13.5 Mt of FW generated in the entire UK FSC (WRAP 2017). In summary, manufacturing FW represents a significant volume of the total FW generated in the FSCs of developed regions of the world. These numbers are discussed in more detail and supplemented with additional data in Section 3.3.

The aim of the research described in this thesis is to investigate feasible, more sustainable solutions for FWM in the UK food industry. This is achieved through:

1. The development of a framework for identification of food waste types and sustainable waste management solutions
2. The identification of qualitative and quantitative attributes that can describe FWM
3. An analysis of the attributes identified to model FWM

The structure of this thesis comprises three main sections: research background and literature review, theoretical research and case studies, and research discussion and conclusions, as depicted in Figure 1-2.

The research background and literature review section comprises five chapters. Chapter 2 provides a research justification and establishes the objectives and scope of the research. An extensive literature review is presented in Chapters 3-5, which discuss ramifications and issues of FW (Chapter 3), possible solutions to manage FW (Chapter 4), and categorisations and tools for FWM (Chapter 5). Chapter 6 provides a brief review of common research methodologies and outlines the methodology adopted to complete the research presented in this thesis.

The theoretical research and case studies section consists of four chapters and presents the research novelty and main research contributions of this thesis. Chapter 7 presents a framework for identification of FW types and their most sustainable waste management solution. Chapter 8 introduces a procedure to model FWM and identifies the quantitative attributes needed for FWM modelling. Chapter 9 provides an analysis of relationships between attributes and information flows to support analysis of different FWM scenarios. Chapter 10 presents case studies with two UK food manufacturers in which the research presented in Chapters 7-9 is used and its applicability and usefulness are demonstrated.

The final section of the thesis provides a research discussion and the main conclusions of the research. In Chapter 11, a summary of the research findings and discussion of the research results obtained are presented. Chapter 12 highlights the main research conclusions and proposes opportunities for further work within this research area as a continuation of this research.

Finally, Appendix 1 shows an example of a FW questionnaire used to identify and categorise FW streams in the food companies participating in the case studies, and Appendices 2-8 present the articles published during the development of the research reported in this thesis.

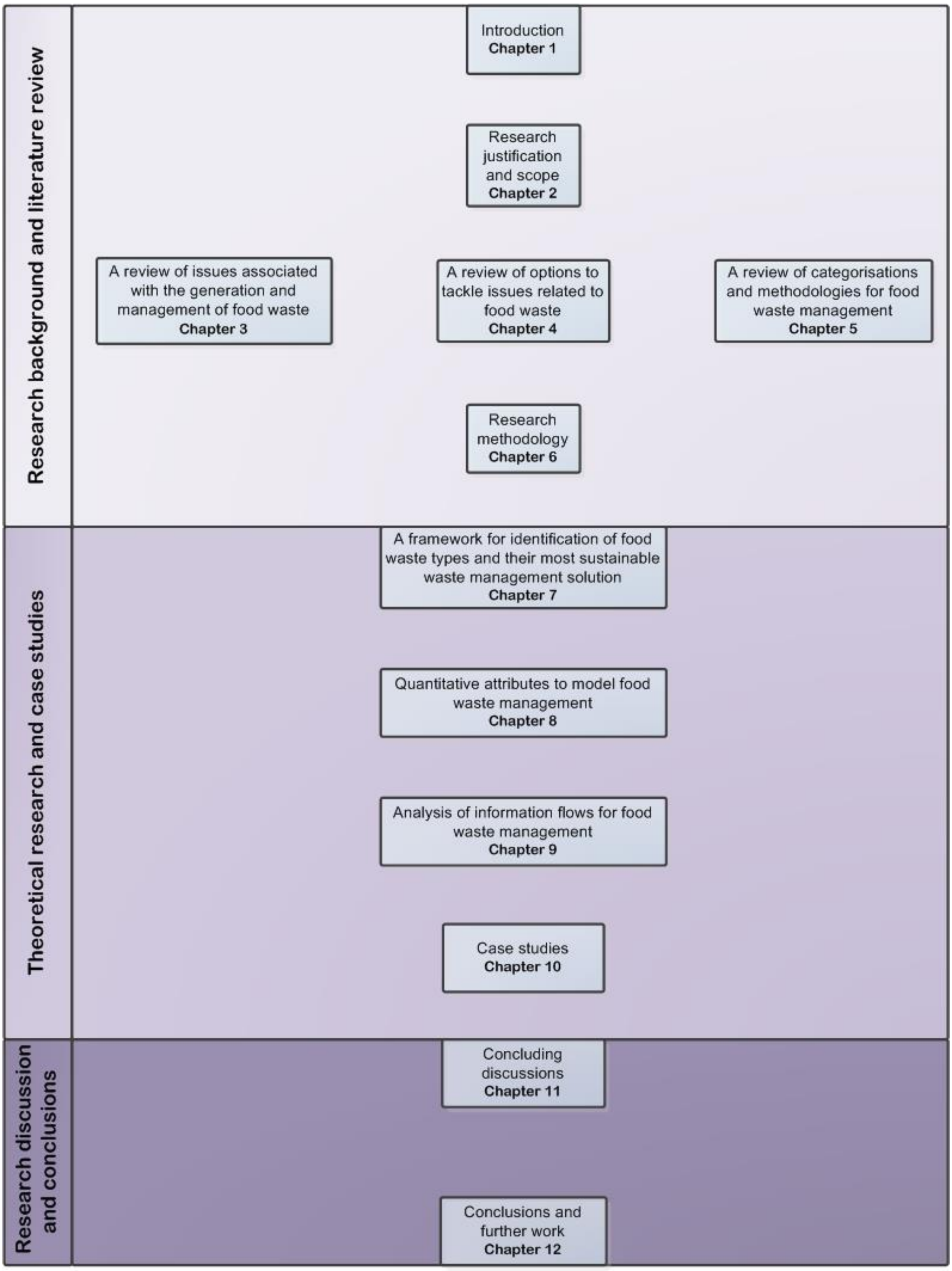


Figure 1-2. Thesis structure

CHAPTER 2 RESEARCH JUSTIFICATION AND SCOPE

2.1 Introduction

This chapter provides a justification and scope of the research presented in this thesis. The research context and questions are described, the research objectives are established and the research scope is defined.

2.2 Research context

The first Millennium Development Goal established following the Millennium Summit of the United Nations in 2000 was "to eradicate extreme poverty and hunger". Although the objectives of halving the proportion of people whose income is less than $1.25 a day and halving the proportion of people who suffer from hunger by 2015 (with reference to 1990) were met (United Nations n.d.), there are still 795 million people suffering from chronic hunger worldwide (FAO et al. 2015). However, it has been reported that the world already produces enough food to feed the entire human population (FAO 2002). The main issue is that large amounts of food are produced for human consumption, but never consumed. The contrast between the number of hungry people in the world and the amount of FW provides an enormous moral problem, and also highlights the importance of this issue to reach global food security.

FW is indeed one of the most challenging issues humankind is currently facing worldwide. It is a global problem that affects all stages of the FSC in both developing and developed areas. It has been estimated that between one-third and one-half of the food produced for human consumption worldwide is never consumed (i.e. between 1.3 and 2 billion tonnes per year) (FAO 2011, Institute of Mechanical Engineers 2013). Although this FW is generated across all stages of the FSC in all countries, previous research shows that in developing countries most FW is created towards the beginning of the FSC (at the farm level) whereas in developed countries the majority of FW is generated at the end of the FSC (at the consumer stage) (Lipinski et al. 2013).

Depending on the size of the food industry, manufacturing FW can amount to a very significant quantity in some developed regions as well. In Europe, the percentage of total FW generated at the manufacturing stage of FSCs is reported to be between 39% for EU-27 (European Commission (DG ENV) 2010) and 19% for EU-28 (FUSIONS 2016), although the latter reference does not include FW diverted to animal feeding or biochemical processing. In the UK, the food industry produces of the order of 5.2 Mt of FW per year, which includes redistributed food, FW diverted to animal feeding and food by-products (Parfitt, Woodham, et al. 2016), out of approximately 13.5 Mt of food wasted in the entire UK FSC (WRAP 2017). UK food manufacturers manage this FW in a range of ways, from more sustainable alternatives such as animal feeding, to less sustainable solutions such as thermal treatments or even landfilling (Lee & Willis 2010, Whitehead et al. 2013).

In addition to this issue, FWM has associated significant economic, social and environmental impacts. The costs associated with these impacts are estimated to be as high as USD 1 trillion for economic costs, USD 900 billion for social costs and USD 700 billion for environmental costs (FAO 2014c). It is imperative to reduce not only the quantity of FW but also the environmental, social and economic ramifications of the FW that cannot be reduced because it is unavoidable (i.e. inedible FW, such as food by-products). This unavoidable FW accounts for 70% of the total industrial FW (Parfitt, Woodham, et al. 2016).

To find the most sustainable ways to manage FW it is paramount to minimise negative impacts and maximise the socio-economic benefits of the processes. In recent years, excellent results have been achieved to obtain value from FW through extraction of some of its valuable compounds, or to obtain energy by means of anaerobic digestion. Other alternatives heavily used in the past but which are hazardous to the environment, such as landfilling and incineration, have fortunately been less favoured, although they are still utilised in some cases.

On the other hand, the growing public and scientific interest in FW has created a number of new approaches, terminologies and methodologies. There is no global agreement on the meaning of the concept of FW, ways to quantify it and measure its impacts, classifications of different types of FW, and optimal procedures to manage FW. There is a need for a better understanding of the shortcomings associated with FWM, and for that a holistic approach is necessary to define concepts and methodologies. Following that, an identification of knowledge gaps is necessary, and finally improvements in management practices can be developed and implemented.

In summary, UK food manufacturers generate large amounts of FW, of which a majority is unavoidable. There is a wide range of ways that food manufacturers use to manage it, including options with significant environmental, economic and social ramifications. It is hypothesised that a systematic framework to analyse FWM scenarios will support food manufacturers to implement more sustainable solutions for FWM.

2.3 Research questions

The main question posed by this research is: *How can food manufacturers minimise the environmental impact and upgrade the socio-economic value of industrial food waste?* In order to effectively address this question, the following questions must be asked:

1. What types of FW are generated within food factories and how can they be systematically categorised?
2. How can food manufacturing companies methodically find the most sustainable solution to manage each FW type?
3. What information is needed to model FWM and consequently estimate the results obtained from the management of a certain FW?

2.4 Research aim and objectives

The overall aim of this research is to investigate the suitability of various technologies and management practices to maximise benefits and mitigate impacts when recovering value from different types of FW generated during food manufacture. In order to achieve this aim, the following objectives have been identified and investigated:

1. Review relevant literature in order to understand how much food is wasted in an industrial context; and identify the types of food being wasted, how they can be managed and what impacts are associated with them.
2. Provide a systematic categorisation of all types of FW.
3. Develop a framework that can be used by food manufacturers to harmonise different approaches to FWM in order to support the identification of the most sustainable solution to manage each type of FW.
4. Analyse the type and range of information needed to model FWM in order to be able to quantitatively estimate the outcomes generated from management of FW so more informed decisions can be made.
5. Apply the ideas generated in the aforementioned objectives to industrial case studies and thus validate them.

Once the research was completed, the research outcomes were examined, the conclusions were highlighted and the findings were reported in this thesis.

2.5 Research scope

The objectives of this research have been used to define the research scope as follows:

1. *Review relevant literature in order to understand how much food is wasted in an industrial context; and identify the types of food being wasted, how they can be managed and what impacts are associated with them.*

An exhaustive review of relevant literature has been carried out in order to define the research in its appropriate context. Chapter 3 provides the most reliable and updated data on FW quantities in the world, Europe and the UK, with a focus on the UK FSC. Chapter 3 also analyses the most important ramifications associated with FWM, with a focus on environmental impacts. Chapter 4 reviews relevant initiatives to tackle FW, introduces the waste hierarchy and discusses the most commonly used waste management practices. Chapter 5 provides a study of different categorisations to characterise FW, and software tools and methodologies to support FWM. As a result of this literature review, the research scope was narrowed to reactive solutions to manage FW at the manufacturing stage of the UK FSC.

2. *Provide a systematic categorisation of all types of FW.*

Following the analysis of existing categorisations of FW, a novel FW categorisation is presented in Chapter 7, which allows the classification of FW types and identification of FW characteristics necessary to select the most sustainable solution for FWM. The categorisation proposed is divided into nine stages, and within each stage the qualitative parameter that better describes the FW analysed must be selected. The FW categorisation is applicable to all types of FW, as defined in Chapter 7, and it is determinative to identify the most sustainable option for FWM.

3. *Develop a framework that can be used by food manufacturers to harmonise different approaches to FWM in order to support the identification of the most sustainable solution to manage each type of FW.*

The novel nine-stage FW categorisation is part of a framework to analyse FW types and opportunities to manage FW sustainably. Chapter 7 provides a novel definition of FW that includes edible and inedible materials associated with food products, drinks, and any food material originally intended to be used for human consumption and not ultimately sold as planned for that purpose. Other materials, such as packaging waste, substances consumed but not ingested (e.g. chewing gum, tobacco) and recreational drugs are out of the scope of this research. Any food that is sold to be consumed by humans, although they may be of low quality or there was no need to consume it (i.e. over-consumption), is also out of the research scope.

The boundaries of food systems are also set in Chapter 7, where different materials that become food and foods that become FW are identified, providing a scope for FW types to be analysed using the FWM framework. A methodology is also presented in Chapter 7 to simplify the use of the FW categorisation and the identification of the most sustainable solution for FWM. Five FWM options have been analysed in detail and included in the FWM framework: redistribution, animal feeding, anaerobic digestion, composting and thermal treatments with energy recovery.

4. *Analyse the type and range of information needed to model FWM in order to be able to quantitatively estimate the outcomes generated from management of FW so more informed decisions can be made.*

Once FW has been defined and categorised, and its most sustainable FWM solution has been identified, an estimation of the results obtained from FWM is necessary. These results can be divided and classified into the three main domains of sustainability: environmental, social and economic outputs. Chapter 8 analyses FWM systems and sustainability implications of FWM, and provides specific lists of quantitative attributes to model FWM. Chapter 9 examines the relationships between the attributes identified, and presents a methodology to assess the information flows between attributes, with the aim of supporting analyses of FWM. Mathematical modelling of relationships between attributes is out of the research scope, but has been discussed and proposed as an extension of the research in Chapter 12.

5. *Apply the ideas generated in the aforementioned objectives to industrial case studies and thus validate them.*

The research ideas presented in Chapters 7-9 have been tested via case studies with two UK food manufacturers: a brewery and a meat-alternative manufacturer. The applicability and usefulness of the research, along with the results generated from the case studies, are presented and analysed in Chapter 10. Limitations of the research identified while undertaking the case studies, such as the need for additional attributes to model FWM systems, have also been discussed in Chapters 10 and 11.

2.6 Chapter summary

This chapter has described the context of the research and the questions that this research addresses. The overall aim and specific objectives have been set, and the objectives have been used to generate the scope of the research. The following three chapters present a review of ramifications associated with FWM, the most common options to manage FW, and relevant categorisations, tools and methodologies useful to support FWM.

CHAPTER 3 A REVIEW OF ISSUES ASSOCIATED WITH THE GENERATION AND MANAGEMENT OF FOOD WASTE

3.1 Introduction

The initial section of this chapter introduces the concepts of 'food security' and 'sustainability' and justifies the important role FW has in both. Secondly, the most reliable and updated data sources have been analysed in order to report quantities of FW generated in FSCs around the world, Europe and the UK, discussing the quality of the data reported. Ramifications of FW have also been identified and measured for global, European and UK FW, categorising environmental, economic and social impacts. The latter part of the chapter presents a comprehensive list of causes behind the generation of FW, classified in the different stages of the FSC, for both developing and developed areas of the world.

Although covering the food sector as a whole, this chapter focuses on the manufacturing stage of the UK FSC in order to fit with the research scope presented in Section 2.5. Environmental impacts have also been assessed in more detail than socio-economic ramifications.

3.2 Overview of food security

The most significant outcome from the World Food Summit on Food Security, held in Rome (Italy) between the 13th and 17th of November 1996, was the adoption of the Rome Declaration on World Food Security, in which the right of every person to have access to safe and nutritious food was reaffirmed. The consequent Plan of Action of the 1996 World Food Summit provided the following definition of food security, which has been widely used since then: "food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 1996). From the previous definition, "all people" means that a state of food security must be global, i.e. cover the entire human population, and consequently the concept 'global food security' is largely used. "All times" refers to the fact that a state of food security must also be sustainable, since the definition of sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development 1987).

Currently, it is estimated that there are 216 million people fewer than in 1990-92 suffering from undernourishment, which is a significant reduction taking into account the increased global population between now and then; nevertheless, 795 million people remain undernourished (FAO et al. 2015). In order to feed these people, and the additional approximate 2.2 billion people who will live on Earth by 2050 (according to projections by Worldometers (2017a), based on 2015 data from the United Nations), both an increase in food production and in food systems efficiency is necessitated. It has been stated that global food supply must be increased by at least 60% due to rising human population, urbanisation and an increase in per capita income, but that this additional food demand can be met with the resources available (Grafton et al. 2015). Cutting FW in half would reduce the gap between calories produced in 2006 and needed in 2050 by approximately 20% (World Resources Institute (WRI) 2013). Additionally, saving just 25% of the current global FW mass and redistributing it would be enough to feed all the undernourished people in the world (Save Food n.d.).

Achieving global food security is a challenge that requires a set of actions to be established and accomplished by numerous actors, including governments, supranational organisations, non-governmental organisations, agriculturists, food businesses, retailers and consumers. Unquestionably, FW plays a crucial role in this global challenge: the FW issue is a key milestone to achieving global food security (Irani & Sharif 2016).

3.3 Quantification of food waste

In order to better understand the FW issue, its magnitude and the type of solutions needed, firstly a quantification of FW is needed. This section provides the most up-to-date and reliable information on FW quantities in the world, Europe and the UK.

Most of the estimates of FW quantities are based on weight (i.e. its mass content). Due to the different water and calorific content of different food products, measuring by weight does not consistently reflect the energy in food products that could have been consumed by people (Lipinski et al. 2013), which could more precisely inform on the number of people that could have been fed, based on a recommended daily intake of between 2,000 and 2,500 kcal. However, there is little availability of data on energy lost due to FW; furthermore knowing the mass of FW provides more valuable information in order to plan FWM, since most of the calculations in FWM modelling are based on mass. Consequently, FW quantification by mass is mostly used in this chapter.

3.3.1 Global food waste

FW is a global problem present in every country in the world. According to a very reliable source and the most oft-quoted estimate, one-third of the edible parts of the food produced for human consumption worldwide never reaches a human stomach, which represents 1.3 billion tonnes of FW per year, out of the total 4 billion tonnes of food produced every year in the world (FAO 2011). However, this number could be even higher: it has also been estimated that the amount of edible FW is between 1.2 and 2 billion tonnes per year (Institute of Mechanical Engineers 2013), although this reference did not specify whether food produced for uses other than for human consumption was considered. According to most recent estimations, global FW amounted to 1.63 billion tonnes in 2011, although this number includes inedible parts of FW (Porter et al. 2016).

1.3 billion tonnes of FW represents 1.5 quadrillion kcal based on energy, which is 24% of all food produced (Lipinski et al. 2013). Including the food explicitly produced for uses other than human consumption (such as animal feeding and biofuel production), the total FW is only 16% based on energy, with half of the food produced worldwide being ultimately consumed by humans (Kummu et al. 2012). Nevertheless, the potential of preventing or better managing this FW is huge: the food currently produced worldwide is enough to feed the entire human population (FAO 2002).

Perhaps unexpectedly, the ratio of *edible FW:edible parts of the food produced* is similar in developing and developed areas of the world (i.e. with low and high Human Development Index (HDI), respectively). Depending on the type of food considered, this ratio ranges between 20% and 50%, based on estimations reported by FAO (2011). A more detailed analysis of the efficiency of the food systems regarding their FW generation based on energy lost in different areas of the world can be seen in Figure 3-1, based on average data from Kummu et al. (2012) and Lipinski et al. (2013). By contrast, edible parts of FW per capita based on mass is reported to be around two times higher in developed countries: in North America and Europe edible FW reaches 280-300 kg/capita per year whilst in sub-Saharan Africa and South and Southeast Asia it is only between 120 and 170 kg/capita per year (FAO 2011).

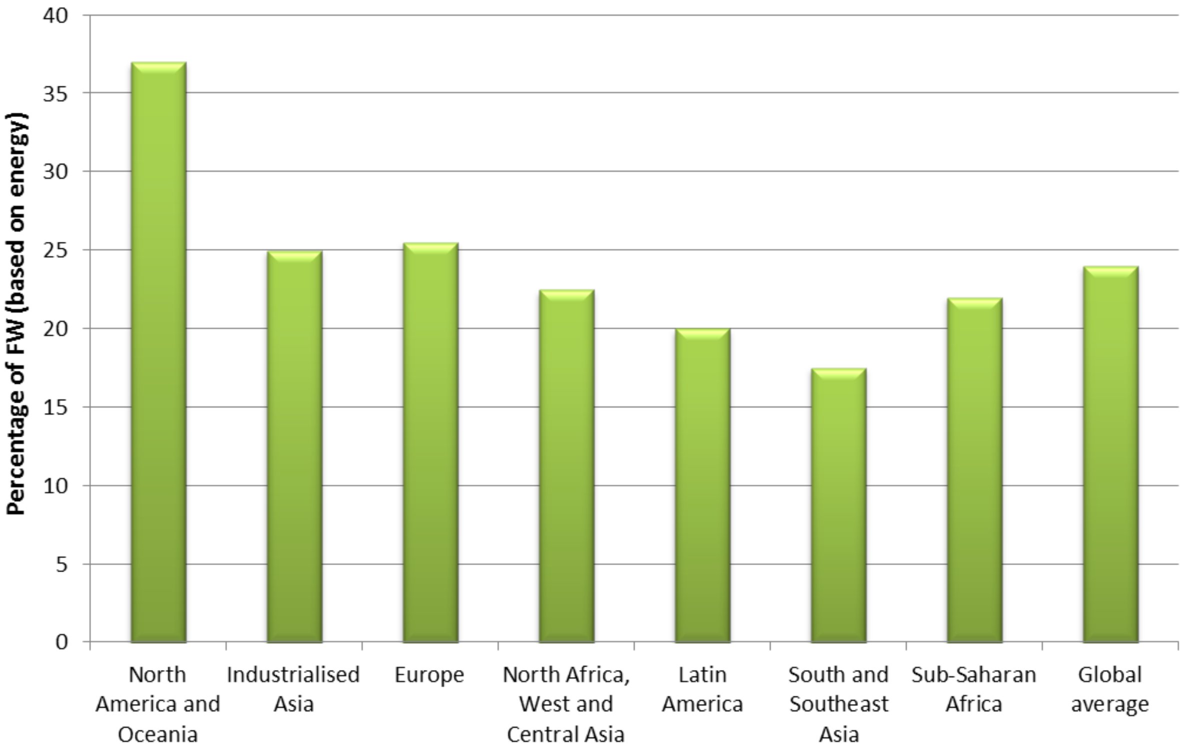


Figure 3-1. Percentage of edible parts of FW (in kcal) in the different regions of the world. Based on average data from Lipinski et al. (2013) and Kummu et al. (2012)

This considerable amount of FW divides unequally amongst the different stages of the FSC in developing and developed regions. As shown in Figure 3-2, edible parts of FW at the consumption stage vary significantly between rich and poor areas: in developed areas, food is typically wasted at the household level (95-115 kg of FW per capita per year in Europe and North-America), whilst in sub-Saharan Africa and South/Southeast Asia most food is wasted at the beginning of the FSC (only 6-11 kg of food is wasted per capita per year in households) (FAO 2011). FW at the processing stage remains proportionally low in all regions, from 2% in industrialised Asia to 9% in North America and Oceania, based on energy.

Figure 3-3 shows the types of food most commonly wasted by energy and weight. The most common food products which become waste are fruits and vegetables (44% of the total edible FW, by weight), followed by roots and tubers (20%) and cereals (19%). Nevertheless, due to the high amount of water and low caloric content, fruits and vegetables represent only 13% of FW by energy. On the other hand, cereal waste contains more than half of the kcal wasted worldwide.

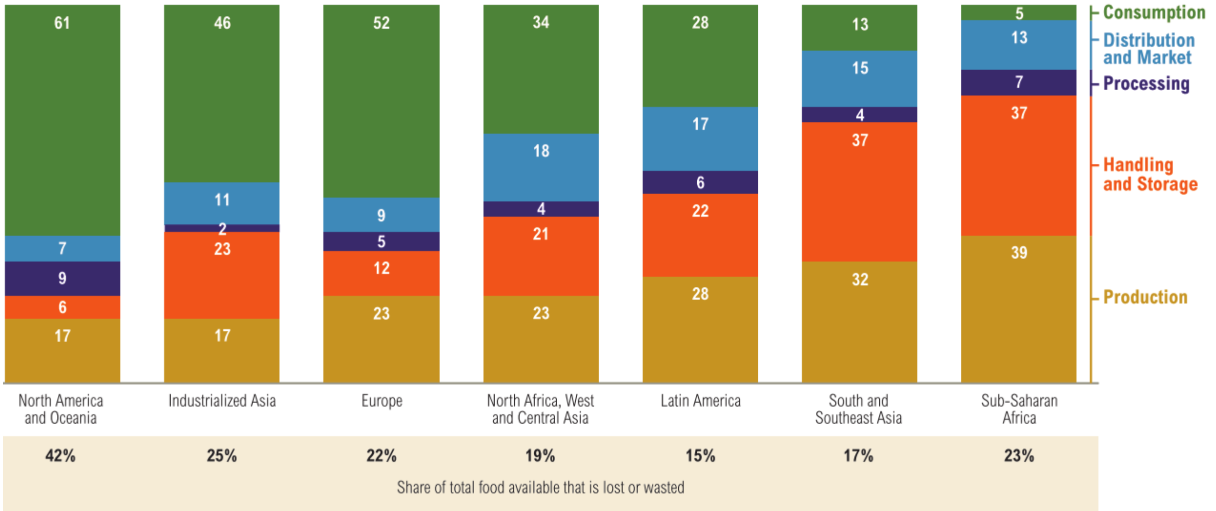


Figure 3-2. Percentage of edible parts of FW (based on energy) at different stages for the FSC for different areas of the world (Lipinski et al. 2016)

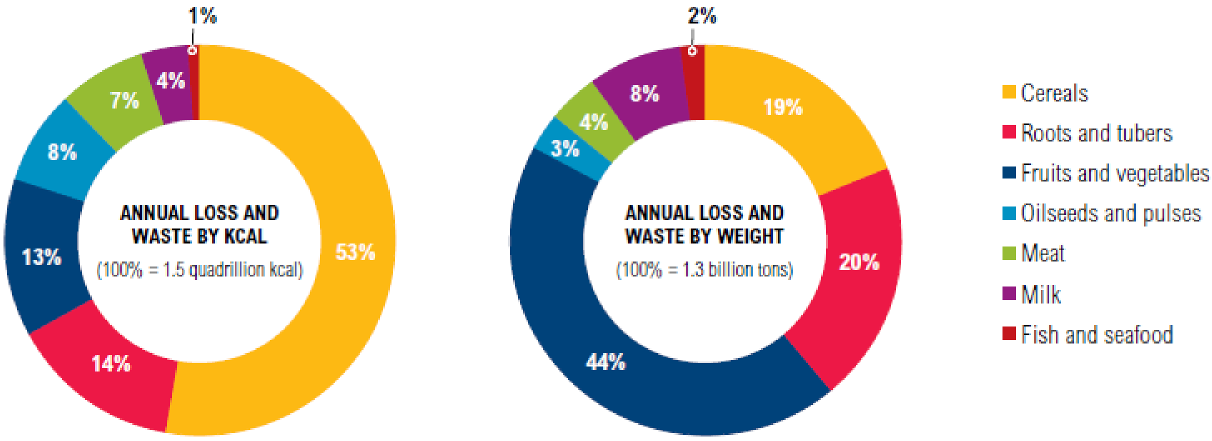


Figure 3-3. Split of FW globally (edible parts only) by types of food (Lipinski et al. 2013)

The variant shares of FW amongst the stages of the FSC in developing and developed regions suggest different reasons and causes for the food becoming waste, which are analysed in Section 3.5. Thus, different solutions must be applied in different areas of the world to reduce their amount of FW. Similarly, the different types of FW suggest that a number of solutions must be used to manage FW in the most sustainable way.

3.3.2 Food waste in Europe

The official quantity of FW generated in Europe is 88-89 Mt, or 173-179 kg per capita (European Commission (DG ENV) 2010, FUSIONS 2016). Nevertheless, the reliability of this number is questionable, and the following considerations must be taken into account:

1. Data from both studies have been collected from a number of sources from different European countries, in which different methodologies and definitions of FW were used.
2. Data used for estimations by the European Commission (DG ENV) (2010) are from 2006, and by FUSIONS (2016) from different years, but mostly from 2012.
3. Estimates by the European Commission (DG ENV) (2010) do not include agricultural FW. FUSIONS (2016) does consider the production stage (which includes agricultural FW), which accounts for 9.1 Mt of FW (although with a high uncertainty). This raises a concern, since very similar total FW were estimated from both sources (89.3 Mt and 87.6 Mt respectively) in spite of this significant difference in scope.
4. Estimates by the European Commission (DG ENV) (2010) are for EU-27, and by FUSIONS (2016) for EU-28.
5. The European Commission (DG ENV) (2010) does not specify if drinks are included in the estimations. FUSIONS (2016) does state that drinks are considered.
6. Both sources consider both edible and inedible parts of FW.
7. The European Commission (DG ENV) (2010) does not specify if food materials sent for animal feeding or to manufacture bio-products are considered in the estimations. FUSIONS (2016) does state that those food materials and drinks are not included in the estimates as they are not considered FW.
8. FUSIONS (2016) explains that its numbers are significantly uncertain: the approximate 95% confidence interval is ±14 Mt (or ±16%); consequently, the range of results within this confidence interval is from 74 Mt to 101 Mt.

Another source estimates a total FW in EU-28 of an average of 123 kg per person per year (i.e. a total 62.5 Mt of FW), of which 80% corresponds to edible materials (Vanham et al. 2015). However, this source highlights that the uncertainty of the data obtained is very high, and that they have used data from only six European countries.

Figure 3-4 divides the total EU-28 FW into the different stages of the FSC according to data from FUSIONS (2016). It can be seen that consumers generate approximately half of the total FW, whilst manufacturing is the second largest source of FW, with 19% of the total. According to Priefer et al. (2016), who also estimated the contribution of each stage of the FSC in total FW generation in each European country, households create around half of the total FW in each country, whilst processing and packaging accounts for 10-15%. The European Commission (DG ENV) (2010) estimated a household FW of 42% of the total FW in the FSC, and a manufacturing FW of 39%, which is significantly higher than figures in the aforementioned references.

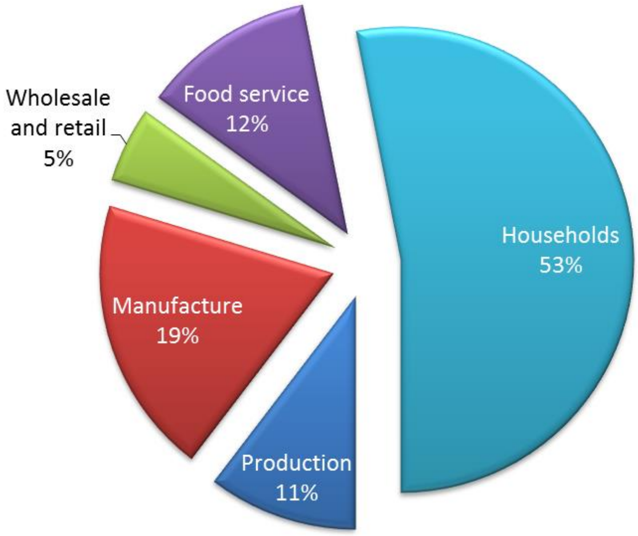


Figure 3-4. Percentage of FW in different stages of the FSC in Europe. Adapted from FUSIONS (2016)

Similarly to global FW, the foods most commonly wasted are fruits and vegetables, and cereals, although by a similar proportion for both categories in most European countries (Priefer et al. 2016). Nevertheless, as indicated by Bräutigam et al. (2014), FW estimations differ significantly, particularly for the manufacturing sector, depending on data sources and assumptions made. Generally, it can be assumed that the split of FW in European FSCs is typical of developed regions.

Keeping in mind the considerations discussed in this section, the estimated total FW per capita in European countries can be seen in Figure 3-5. UK FW generation (≈ 230 kg per capita per year) is higher than EU12, EU15 and EU27 average data, which ranges between 160 and 190 kg per capita per year. In fact, UK's absolute FW level is the highest of any European country (European Commission (DG ENV) 2010); nevertheless, it is important to consider that the UK has carried out very precise quantifications of FW, and therefore real FW amounts in other nations may be higher. Interestingly, the Netherlands produces the highest amount of FW per capita in Europe, with near 600 kg per capita per year. A notable reason for this is the large size of the food manufacturing sector in the Netherlands; in fact, the Netherlands is the world's second-largest exporter of food and agriculture products (Hollandtrade.com n.d.). Considering the ratio of *FW in the manufacturing sector/food production* the Netherlands falls into third position (12-13%), and the UK FW level (3%) is lower than the EU27 average (5%) (Figure 3-6). This highlights the importance of the size of the food industry when comparing FW levels from different countries.

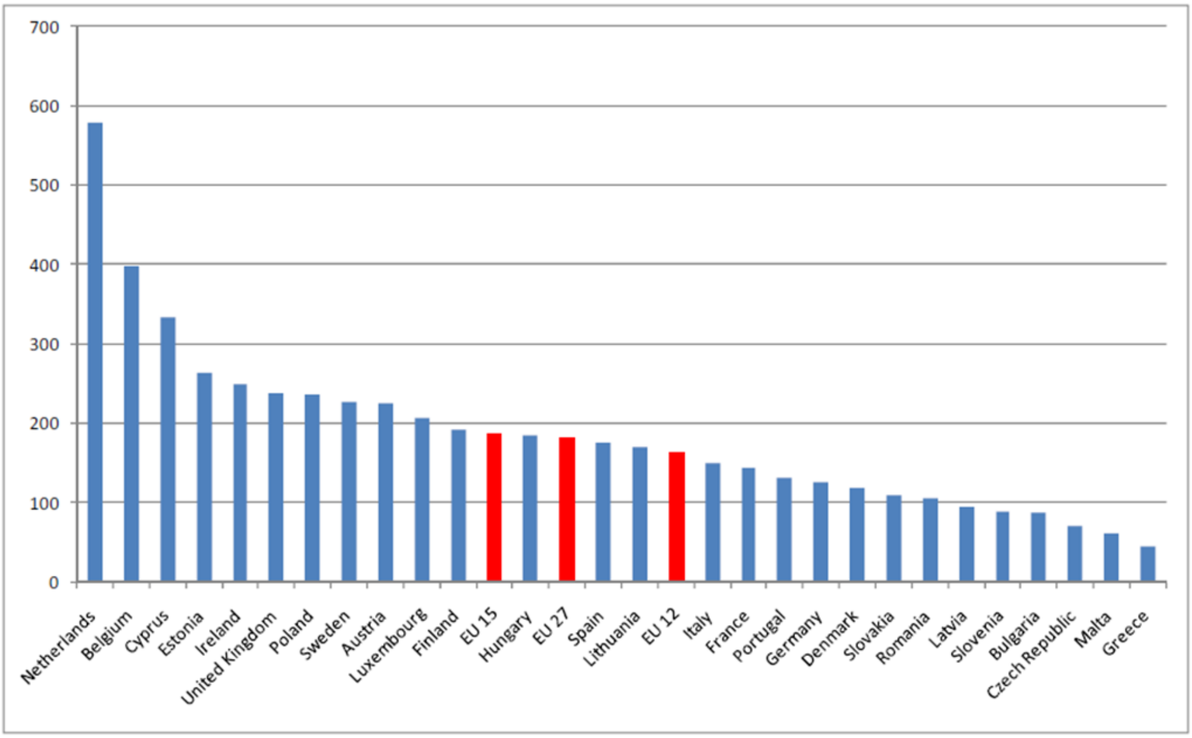


Figure 3-5. FW in European countries per capita (kg per year) (European Commission (DG ENV) 2010)

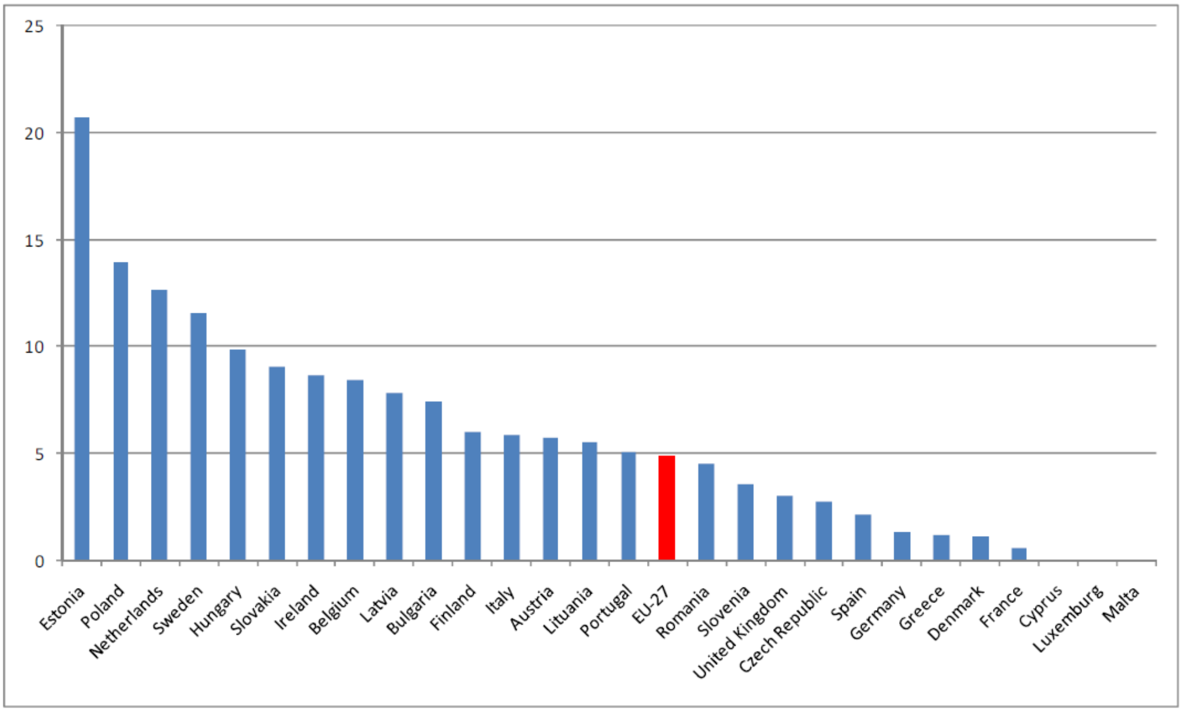


Figure 3-6. Percentage of FW in the manufacturing sector / food produced (European Commission (DG ENV) 2010)

In spite of the high variability in estimations and data from different countries, it can be assumed that manufacturers contribute significantly to FW quantities in Europe. The high variability of FW proportions in the industrial stage of developed nations' FSCs can be explained by a number of reasons, including different manufacturers' efficiencies, size of the food industry sector in the region, type of food predominantly produced (e.g. perishable foods or preserved foods), proportion of food imports and exports in the sector, amount of FW generated in other FSCs' stages, different regulations and government encouragement to reduce FW, and the existence of food charities to manages surplus food.

3.3.3 Food waste in the UK

The UK has been making significant efforts over the last years in order to precisely measure FW levels and reduce them. The Waste and Resources Action Programme (WRAP), a charity organisation that aims to implement a more resource efficiency economy in the UK, is leading a large number of initiatives to tackle FW and has provided most of the UK FW estimates.

The UK generates around 10 Mt of FW per year, of which 60% could have been avoided (i.e. it corresponds to edible parts of food) (WRAP 2017). Previous estimations indicate that FW has been reduced in the UK FSC, since the preceding calculation estimated 15 Mt of FW per year (WRAP 2015). However, the most significant difference in both studies is that WRAP (2015) includes 3 Mt of FW in the production stage of the FSC, which has been excluded in WRAP (2017) because it was not considered a robust estimation. Additionally, more precise calculations and estimations have been used in the latter report.

Other analyses also seem to indicate that FW has been reduced, for instance WRAP (2017) assessed its preceding estimates and reported a reduction in post-farm-gate FW of around 11%, or 1.25 million tonnes, between 2007 and 2015. The Department for Environment, Food and Rural Affairs (Defra) estimated that the FW generated by manufacturers, wholesalers and retailers was almost halved between 2002-2003 and 2009, down 49% (Defra 2013). Nevertheless, there is a lack of reliable data from sources prior to the 2012-2013 period, so this information should be considered with caution.

Yearly FW generated in the different stages of the FSC can be seen in Figure 3-7 and is discussed in the following sub-sections. The data are from 2011-2015, reported by WRAP (2017). It must be noted that data for the production stage are from an estimate from 2004 and is not considered a robust estimation, and manufacturers also generate a large amount of FW that goes to animal feeding and other industries, which are not included here because

WRAP does not consider them FW. Furthermore, WRAP does not include FW redistributed for charitable purposes, used for animal feeding and synthesis of bio-products or rendering in their measurements, so total amounts of FW are higher, particularly from food manufacturers. Food disposed of into sewers is only included for household FW. Food wasted outside of the UK in the production of food imported into the UK is also excluded, which would most likely amount to a large figure, since the UK currently imports over 50% of its food and feed (Ruiter et al. 2015). A detailed analysis of FW quantities in each stage of the FSC can be found below.

3.3.3.1 Production

WRAP has been reporting an approximate figure of 3 Mt for on-farm FW (e.g. WRAP (2013), WRAP (2014), WRAP (2015)), although this number is based on a 2004 report by the Environment Agency (2004), and therefore is considered outdated and not a robust estimation. WRAP is currently working towards a new, more reliable estimation which will be published in 2018 (WRAP 2017). It must also be noted that WRAP usually refers to primary production as on-farm, and therefore it is unclear whether the new estimates will include measurements of FW in other primary production activities such as aquaculture and fisheries.

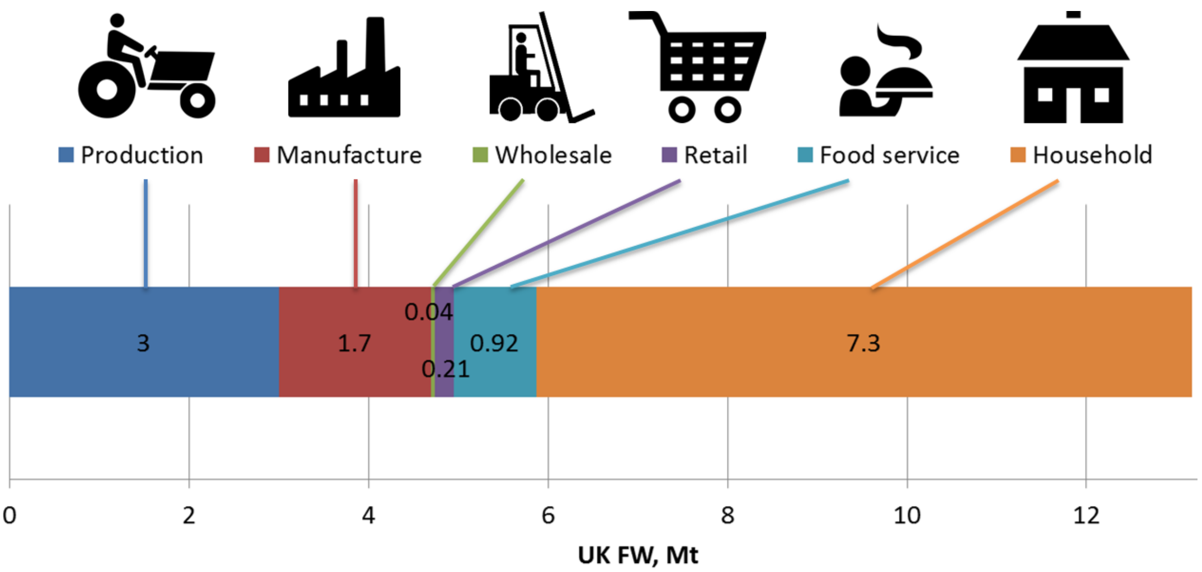


Figure 3-7. Quantity of FW generated in the different stages of the UK FSC according to WRAP data, in Mt

3.3.3.2 Manufacture

Food manufacturers generate 1.7 Mt of FW, according to WRAP's estimations from data collected in 2014-2015 (Parfitt et al. (WRAP) 2016). This is a significant reduction from the 3.9 Mt of FW reported in 2011 (Whitehead et al. (WRAP) 2013), although Parfitt et al. (WRAP) (2016) reported that only 0.2 Mt of FW have been really prevented, the rest being material associated with food production (such as water, soil and bedding) that was previously added to the FW figure (1.8 Mt), and 90,000 t of FW that was double counted. In 2006, it was estimated to be 2.6 Mt (Lee & Willis (WRAP) 2010), although the methodology used and data coverage were significantly different to more recent studies (Whitehead et al. (WRAP) 2013). In contrast, Defra (2013) estimated that FW at manufacturing level dropped by 43% between 2002-2003 and 2009, but this estimate is outdated and based on old methodologies, so it was not considered a robust estimation.

A majority of FW is animal based: 31% of the total FW corresponds to meat, poultry and fish, and 20% to dairy products; both FW categories carry a high environmental and economic footprint, as explained in Section 3.4.3. From the rest, the most significant types of FW are ambient products (11%), alcoholic drinks (9%), and fresh fruit and vegetable processing (8%) (Parfitt et al. (WRAP) 2016). 53% of the total FW is considered to be formed of edible materials (WRAP 2017).

Nevertheless, in addition to the aforementioned 1.7 Mt of FW, 2.8 Mt of food by-products were sent to animal feeding (2.2 Mt) and rendering (0.6 Mt), and 0.7 Mt of food surplus was redistributed (42 kt) or sent to animal feeding (0.6 Mt) (Parfitt et al. (WRAP) 2016). WRAP does not consider these materials as FW, but depending on the definition of FW used they could be included in the FW concept, as discussed in Section 7.2, which proposes a new definition of FW. Accounting for all these materials, 5.2 Mt of FW are generated per year by food manufacturers, of which 70% is unavoidable FW (i.e. inedible food materials). Adding these food materials and the estimate of 3 Mt of FW by producers to the previously reported 10 Mt of FW in the FSC, manufacturers generate nearly one-third of the total FW of the UK FSC.

Parfitt et al. (WRAP) (2016) did not assess other types of waste linked to food manufacturing activities, but according to previous reports, food manufacturers generate an approximate 0.5 Mt of packaging waste and 0.5 Mt of other waste per year (Whitehead et al. (WRAP) 2013, WRAP 2014). Additionally, 1.8 Mt of sludge from on-site treatment and site cleaning is generated every year (Parfitt et al. (WRAP) 2016).

3.3.3.3 Wholesale

Wholesalers generated 43,000 t of FW in 2015, with an additional 225 t of animal by-products sent to rendering, 300 t redistributed and 30 t diverted to animal feed (Parfitt & Parry (WRAP) 2016). This is a significant increase from the 17,000 t of FW reported in 2011, based on an estimation from a 2009 survey carried out by Defra combined with IGD data (Whitehead et al. (WRAP) 2013); however (Parfitt & Parry (WRAP) 2016) claims that both estimations are not comparable, due to different methodologies used and data coverage. The estimation of FW from wholesalers in 2015 included specialist wholesale markets and 'cash and carry' wholesalers, and excluded delivered grocery wholesalers, delivered foodservice wholesalers and retail street markets.

3.3.3.4 Retail

In the period 2014-15, retailers generated 210 kt of FW per year, with an additional food surplus of 32 kt, of which 27 kt were sent to animal feeding and 5 kt were redistributed (Parfitt et al. (WRAP) 2016). This is a significant reduction from 400 kt of FW generated at the retail level in 2011 (Whitehead et al. (WRAP) 2013). This level had already dropped by 69% between 2002 and 2009 (Defra 2013), however similarly to the analysis of other stages of the FSC, previous estimations may not be reliable and comparable to the most up-to-date numbers.

The most commonly wasted food products in this stage are bakery (32% of the total FW), fresh produce (26%), dairy and eggs (13%) and pre-prepared meals (9%), which are wasted mainly due to product damage or product passing its use-by or best-before date (Parfitt et al. (WRAP) 2016).

Parfitt et al. (WRAP) (2016) did not assess types of waste such as packaging waste, but according to previous reports, retailers generated an additional 1.2 Mt of packaging waste in 2011 (WRAP 2014).

3.3.3.5 Food service

The latest data reported in the food service sector is from Oakdene Hollins et al. (WRAP) (2013), which used data collected from 2009 to 2013. Staff catering, healthcare, education, services, restaurants, quick service restaurants, pubs, hotels and leisure are the major sectors in this stage. It is estimated that they generate 0.92 Mt of FW per year, of which 45% arises from food preparation, 34% from consumer plates and 21% arises from spoilage.

These numbers exclude drink waste, which is likely to be a significant amount. Packaging waste accounts for 1.3 Mt, and other wastes generated in the food service stage (such as kitchen paper) for 0.66 Mt.

Nevertheless, it is expected that this quantity has been reduced since those numbers were reported. As an example, the Hospitality and Food Service Agreement (HaFSA) was endorsed by over 230 signatories, representing about 25% of the sector, in order to reduce FW in the food service sector. HaFSA was launched in 2012, and in three years a significant amount of FW was prevented by the signatories (between 11,600 and 24,000 tonnes, not clearly reported) (WRAP n.d.).

It has been reported that 40% of FW generated within this stage arises in restaurants and pubs and 26% from the education and healthcare sectors. 75% of FW is edible, and the remaining 25% consists mainly of fruit and vegetable peelings. 40% of the total FW corresponds to potato and potato products, bread and bakery, pasta and rice (Oakdene Hollins et al. (WRAP) 2013).

3.3.3.6 Household

Households generate about half of the total FW in the UK: in 2015, consumers wasted 7.3 Mt of food at their homes, 75.2 kg per person per year (Quested & Parry (WRAP) 2017). This is an increase of 0.3 Mt of FW from 2012 (Quested et al. (WRAP) 2013). The 7.3 Mt of FW in 2015 ends a reduction of household FW in previous years: 8.3 Mt in 2006/07, 7.2 Mt in 2010 (Quested & Parry (WRAP) 2011) and 7 Mt in 2012 (Quested et al. (WRAP) 2013).

Out of the 0.3 Mt increase in FW between 2012 and 2015, 0.2 Mt corresponded to edible parts of the food, which has increased from 4.2 Mt to 4.4 Mt, which is the FW that could have been consumed (namely avoidable FW). 1.3 Mt of FW is possibly avoidable, and 1.6 Mt is unavoidable FW. Household FW is found in the following streams: kerbside (residual, collections targeting FW and FW contaminating dry recycling), Household Waste Recycling Centre (HWRC) residual waste, FW disposed to sewer, home composted and fed to animals (Quested & Parry (WRAP) 2017).

Quested & Parry (WRAP) (2017) did not categorise different types of FW generated. According to the previous report (Quested et al. (WRAP) 2013), the most commonly wasted food products at the household level are fresh vegetables and salads (23% of the total), drinks (18%) and fresh fruit (13%). Considering the avoidable FW only, fresh vegetables and salads and drinks remain as the two most wasted products, but bakery takes third place in this list.

3.3.3.7 Others

This category includes FW generated in the FSC but not belonging to any stage previously described. For instance, it has been reported that 0.1 Mt of food was wasted by consumers out of home in 2012, e.g. in litter bins and street sweepings (WRAP 2017, Quested & Parry (WRAP) 2017).

In 2008 the FW generated during distribution was estimated to be 4000 t, with a more significant packaging waste of 85,000 t (Lee & Willis (WRAP) 2010). In addition to being an outdated estimate, this value was scaled up by WRAP from only one major supermarket's company data. In any case, it is reasonable to assume that this FW is insignificant compared to the total FW in the FSC.

3.4 Assessment of impacts related to the food waste issue

FW has very significant economic, social and environmental ramifications, which are associated with the creation of food products, their distribution and their treatment once they have become waste. These costs have been estimated to be USD 2.6 trillion annually, roughly equivalent to the GDP of France (FAO 2014c). This section reviews the most updated and reliable data to quantify impacts caused by FW, with a focus on environmental ramifications.

3.4.1 Global impacts

FW has an associated carbon footprint of between 3.3-3.5 Gt CO_2eq per year, more than the total greenhouse gas (GHG) emissions of Russia, according to FAO (2013a) and FAO (2014c), and 2.2 Gt CO_2eq per year according to Porter et al. (2016). Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the most significant GHGs at agricultural level; carbon dioxide is the most important GHG in the rest of FSC, principally due to fossil energy use (Garnett 2011). Other gases that present a greenhouse effect are hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) (Carbon Trust 2012). Due to their high levels of cereal waste, Asia is the region with the highest carbon footprint; however, the highest carbon footprint per kg of FW corresponds to meat (FAO 2013a).

70% of the total water consumed worldwide corresponds to agricultural activities (Worldometers 2017b), which is 2.5 trillion m^3 (Institute of Mechanical Engineers 2013). 250 km^3 of water per year are used to produce food that ends up being wasted, an average of 38,000 l per capita per year (FAO 2013a). This is 5 times the blue water footprint (which refers to the water footprint of water in aquifers and water courses) for consumption of agricultural products in USA. A more recent estimation raises this number to 300 km^3 of water for irrigation and an additional 5 km^3 as drinking water uptake of animals (FAO 2014c). FAO (2014d) reports a very similar figure of 306 km^3 of water use related to FW. The products with the highest blue water footprint are cereals (52%) and fruits (18%), since they are two of the types of products most commonly wasted (FAO 2013a). Estimates of water footprints vary considerably per kg of FW, although it is generally agreed that animal products require significantly more water than plant-based products (Institute of Mechanical Engineers 2013). Kummu et al. (2012) estimated that the proportion of water lost due to FW represents a 24% of the total water used for food production globally, and reports a water use for FW of 27 m^3 per person per year, i.e. total water use for global FW of about 200 km^3 per year.

Global FW also had an associated land occupation of 1.4 billion hectares in 2007, near 28% of the total agricultural land area of the world and a larger area than Canada's total surface (FAO 2013a). This is about 2000 m^2 per capita per year. Meat and milk present the highest impact by mass of FW, and they occupy principally non-arable land (FAO 2013a).

All aforementioned environmental impacts include impacts associated with both edible and inedible parts of food, but exclude FW used to feed animals (except Institute of Mechanical Engineers (2013), who did not specify). FW environmental impacts have an associated global cost estimated at USD 700 billion (FAO 2013a)

In addition to environmental impacts, FW has an estimated economic cost of USD 1 trillion as bulk-trade value (FAO 2014c). Segrè et al. (2014) proposed a useful theoretical framework for quantitative studies on the economic impacts of FW, conceptualising FW in terms of micro, macro and non-economic conditions, although no new estimate of the economic costs of FW was given.

The social costs of FW include a broad range of impacts, such as increased public costs, creation and aggravation of conflicts, jobs loss, livelihood loss, people's health damage and noise. It has been estimated that FW social impacts have an associated global cost of USD 900 billion (FAO 2014c).

3.4.2 Impacts in Europe

According to the European Commission (DG ENV) (2010), in the EU27 FW generates 170 Mt of CO_2eq/year, with an average 1.9 t of CO_2eq per t of FW. Nevertheless, FUSIONS (2015) estimated higher FW-related emissions based on two studies: 227 and 304 Mt of CO_2eq/year, although giving more credit to the former number due to the methodology used.

The blue water footprint for FW, excluding animal feeding and industrial uses of waste, is 18 m^3/capita per year (Kummu et al. 2012), which would be around 9 km^3 of water per year for the EU28. This is a proportion of 31% of water lost due to FW of the total water used for food production in Europe. Vanham et al. (2015) estimated an agricultural water footprint of production of avoidable FW from EU consumers of 52 km^3 per year of green water (i.e. water footprint with regard to the rainwater use) and 5 km^3 per year for blue water, with meat waste as the largest contributor to the water footprint (18.8 and 1.2 km^3 per year for green and blue water footprint respectively).

Kummu et al. (2012) estimated a cropland use due to FW of 334 m^2 per capita per year (about 26% of the total cropland use) and a fertiliser use of 3.9 kg per capita per year (15.8% of the total fertiliser use). According to Vanham et al. (2015), the nitrogen footprint of production of avoidable FW is 1.34 Mt N per year, and meat waste provides the largest nitrogen footprint, followed by milk and cheese. Grizzetti et al. (2013) estimated that globally 2.7 Mt N are lost per year due to FW at consumption, and that the nitrogen delivered to the environment associated with the global FW is 6.3 Mt N per year.

The European Commission (DG ENV) (2010) also assessed other indicators of European FW, such as acidification (2563 kt SO_2eq/year), photochemical oxidation (666 kt NMVOCeq/year) and resource depletion (261 Mt/year), although end-of-life impacts (i.e. environmental impacts of FWM) were not considered. FUSIONS (2015) reported that for carbon footprint, acidification and eutrophication, most of the emissions across the life cycle are related to the production of food that ends up wasted.

The economic costs of the edible parts of FW in EU-28 were estimated at around €143 billion in 2012, with two-thirds of the economic costs associated with domestic FW (around €98 billion), and €13 billion related to the food manufacturing sector (FUSIONS 2016). These costs refer to the value of the food that has been wasted within the given sector, thus the value of FW per kg increases towards the end of the FSC. Social costs related to FW in Europe have been recognised, such as loss of jobs and increased food prices, but not measured.

3.4.3 Impacts in the UK

The FSC accounts for about a fifth of GHG emissions in the UK, between 130 and 170 Mt of CO_2eq per year (Chapagain & James (WRAP) 2011, Whitehead et al. (WRAP) 2013). Defra (2016) estimated annual emissions of 70 Mt of CO_2eq per year, although this excludes emissions from food packaging, food waste, land use change, electricity use in food manufacturing, road freight transport and emissions from heating water for washing up or dishwashers at home. At least 20 Mt of the FSC GHG emissions comes from FW (WRAP 2017), although the exact number is unclear. This is a reduction from the 25 Mt reported in 2010, of which 78% was associated with avoidable FW and the rest with possibly avoidable (unavoidable FW was not considered) (Chapagain & James (WRAP) 2011). This reference adds 7.6 Mt of CO_2eq per year for emissions associated with land use change from avoidable FW not included in the 25 Mt reported above. In terms of types of FW associated with large impacts, the foods associated with a higher cradle-to-retail carbon footprint are milk, fresh beef, chilled ready meals, frozen red meat and pre-packaged sandwiches (Fisher et al. 2013), although it is important to notice that this does not include the use phase and end-of-life. At retail and manufacturing levels, 250,000 tonnes of CO_2eq are generated each year only to manage FW, not including emissions of FW in its life cycle (Whitehead et al. (WRAP) 2013). Emissions related to disposal of food correspond to only 2% of the total GHG emissions of the UK FSC, excluding land use change (according to Garnett (2011), based on estimations of Garnett (2008)).

Chapagain & Orr (WWF-UK) (2008) stated that agricultural products have a water footprint of 74.8 km^3/year, which is 73% of the total UK water footprint. Whitehead et al. (WRAP) (2013) provides a similar figure of 70 km^3/year or 70% of the total UK water footprint. 62% of this water footprint is related to agricultural products from abroad (Chapagain & James (WRAP) 2011). Regarding FW, the total water footprint is 6.3 km^3/year, with 86% associated with avoidable FW and 14% with possibly avoidable FW (Chapagain & James (WRAP) 2011), although this reference did not assess the water footprint of unavoidable FW and attributed it to actual food consumption. 6.3 km^3/year seems a too-large number for the water footprint of the UK, since the European water footprint is estimated to be 9 km^3/year (Section 3.4.2); this emphasises the need for a standardised methodology to assess environmental impacts of FW. Although there is not a consensus about the exact water footprint per mass of different food products, it can be assumed that it is generally higher for animal products, due to the high water footprint of the feed consumed by the animal throughout its lifetime (Fisher et al. 2013).

It is estimated that the 10 Mt of post-farm gate FW has a value of over £17 billion per year, of which £13 billion is associated with FW from the household level, £2.5 billion with the food service stage, £1.2 billion with manufacturers, and £0.8 billion with wholesalers and retailers (WRAP 2017). Quested et al. (WRAP) (2013) estimated that the value of avoidable FW from the household level was £12.5 billion in 2012, which seems to indicate that the real value of the FW is attributable to its edible part. Whitehead et al. (WRAP) (2013) suggested an alternative estimate of £3.71 billion for manufacturers, £20 million for wholesalers and £510 million for retailers, based on an estimated value of FW of £950/t for manufacturers, £1000/t for wholesalers and £1200/t for retailers. The estimated costs for manufacturing include the cost of ingredients, energy and water costs, disposal costs and lost profit, of which the cost of ingredients, energy and water costs represent nearly 80% of the total cost. For retailers, an additional 20% of the total manufacturing cost was assumed, whilst for wholesalers the estimated cost was assumed to be near that of manufacturers.

The social impact of FW in the UK has not been quantified, although it has been recognised. For instance, Priestley (2016) discussed how FW could have been redistributed and used to feed 'people in need', and highlighted the work of organisations and food banks, such as The Trussell Trust, to address this issue.

3.5 Evaluation of the causes behind the generation of food waste in the FSC

As stated in Section 3.3.1 the proportion of food which ends up being wasted at different stages of the FSC varies significantly between developed and developing areas of the world. This leads to the hypothesis that there must be different reasons as to why food is wasted in different regions. In fact, FW is generated principally at the beginning of the FSC in developing countries (during production) due to a lack of technology, infrastructure, proper storage facilities and 'know-how'. On the other hand, food is generally wasted at the end of the FSC in developed countries (during consumption), as a result of buying and preparing an excessive amount of food (Institute of Mechanical Engineers 2013).

An extensive collection of causes of food becoming waste, divided by stages of the FSC and by developing and developed areas, can be seen in Table 3-1 to Table 3-6. The lists of causes are based on the author's knowledge and the following sources: Van der Vorst (2000), WRAP (2007), Mena et al. (2011), FAO (2011), Barilla Center for Food & Nutrition (2012), Institute of Mechanical Engineers (2013), FAO (2014b) and Raak et al. (2016).

Table 3-1. Causes of generation of avoidable FW at the production stage

Developing areas	Developed areas
Climatic factors	Climatic factors
Limited technical, financial and managerial resources	Over-production caused by poor forecasting methods, changeable demand or lack of information sharing with other agents
Premature harvests due to urgent need for food or to obtain income	Quality standards (usually aesthetic) established by other stages of the FSC
Inefficient harvesting methods	Clauses that penalise farmers who do not meet agreed quantities of food harvested
Inadequate infrastructure for transportation of food	
Lack of appropriate storage facilities	
Infestations caused by a lack of use/availability of pesticides	
Spillage	

Table 3-2. Causes of generation of avoidable FW at the manufacturing stage

Developing areas	Developed areas
Lack of technology and 'know-how' to process food properly	Inefficiencies in production processes
Lack of appropriate storage facilities	Damage to food during processing (e.g. burnt food)
Spillage	Clauses that give retailers the right to return unsold products
Lack of use of food preservatives	Lack of awareness about the FW issue
	Over-production caused by poor forecasting methods, changeable demand or lack of information sharing with other agents
	Food not used in time (spoilt or passed expiration date)
	Poor inventory management
	Quality standards established by regulations (e.g. sterility, chemical composition)
	Other quality standards (usually aesthetic) established by other stages of the FSC
	Concerns about food safety and traceability

Table 3-3. Causes of generation of avoidable FW during distribution

Developing areas	Developed areas
Inadequate roads and vehicles for transportation of food Improper loading and offloading Problems to transport products in proper conditions (e.g. cold chain) Inefficiencies in distribution systems Spillage	Spoilage of food due to the need of transporting it long distances (e.g. food importation)

Table 3-4. Causes of generation of avoidable FW at the retail stage

Developing areas	Developed areas
Lack of appropriate storage facilities Overcrowded and not hygienic markets Employees not following procedures for stacking and shelving	Displaying large quantities and a wide range of foods Over-purchase of food caused by poor forecasting methods or changeable demand Aesthetic standards demanded by consumers which are not met Employees not following procedures for stacking, shelving and stock rotation

Table 3-5. Causes of generation of avoidable FW at the food service stage

Developing areas	Developed areas
	Excessive size (and lack of offer for different sizes) of food portions served Lack of acceptance to take the leftovers home Damages during cooking (e.g. burnt food) Food not used in time (spoilt or passed expiration date) Poor planning before buying food

Table 3-6. Causes of generation of avoidable FW at the household stage

Developing areas	Developed areas
Improper storage of food	Marketing strategies by retailers that encourage buying more food than necessary (e.g. offers such as 'buy one, get one free')
	Too much food cooked or served
	Damages during cooking (e.g. burnt food)
	Poor process control (e.g. inefficient fruit peeling where part of the pulp is discarded with the skin)
	Food not used in time (spoilt or passed expiration date)
	Confusion concerning 'use-by' and 'best-before' dates
	Poor planning before buying food
	Improper storage of food
	Limited knowledge of how to use leftovers
	Not liking the food prepared
	Underestimation of the real value and impacts of FW (e.g. high incomes are linked to larger amounts of FW)

In summary, food is wasted in every region of the world, from developing to developed areas, but due to very different reasons. For the manufacturing stage of developed FSCs, where this research focuses as explained in Section 2.5, there are a number of reasons as to why food manufacturers waste food, including poor processing systems, over-production and strict quality standards.

3.6 Chapter summary

This chapter has evaluated the extent of the problem of FW, firstly putting it into the context of food security, and then analysing how much FW is created and what the ramifications associated with it are. Global, European and UK FSCs have been assessed, concluding that both developing and developed areas of the world are affected by the FW issue, but in different stages of the FSC and due to different reasons. In the UK, only 1.7 Mt of FW has been allocated to the food industry; however there is an additional 3.5 Mt of food materials that are not sold for human consumption, which proves that the FW issue is of significant importance for food manufacturers. Considering these food materials, manufacturers generate nearly one-third of the total FW of the UK FSC.

Additionally, ramifications of the FW issue have been identified and classified into environmental, economic and social impacts. Focusing on environmental impacts, FW ramifications have been quantified, concluding that the FW issue has an enormous negative impact. Finding ways to minimise these FW impacts is paramount to increasing the sustainability of food systems.

CHAPTER 4 A REVIEW OF OPTIONS TO TACKLE ISSUES RELATED TO FOOD WASTE

4.1 Introduction

The initial section of this chapter reviews the most significant initiatives implemented by global, European and UK organisations to tackle the FW issue, with a main focus on the efforts of the UK. Next, management options to deal with FW are described and discussed, classifying them according to the food waste hierarchy depending on their sustainability performance. The latter part of the chapter uses the most reliable and up-to-date estimates to quantify the use of each solution for FWM across all stages of the UK FSC. The analysis presented in this chapter justifies the delimitation of the scope of this research presented in Section 2.5.

4.2 Initiatives to tackle food waste

Due to the rising awareness of the importance of FW, several organisations have launched different initiatives to tackle the FW issue. A number of them aim to raise consumer awareness to reduce FW, particularly at the domestic level, but there are also initiatives to explore alternative ways to manage FW. This section details the most relevant organisations and campaigns that tackle this issue in the world, Europe and the UK.

4.2.1 Global initiatives

The Food and Agriculture Organisation of the United Nations (FAO) has published several reports over the last years to improve people's awareness of the FW problem. Together with the United Nations Environment Programme (UNEP) and the Messe Düsseldorf, FAO created the *Save Food* initiative, whose aims are to raise awareness of FW and encourage dialogue between industry, research, politics and civil society. *Think.Eat.Save* is one of the most noticeable campaigns of the Save Food initiative. In addition, the *Zero Hunger Challenge*, an initiative from the United Nations to tackle hunger in the world, has as its third target to "adapt all food systems to eliminate loss or waste of food".

The United Nations also set the Sustainable Development Goals (SDGs) in 2015, which includes 17 objectives as part of a new sustainable development agenda. Goal 12.3 is to halve per capita global FW at the retail and consumer levels and to reduce food losses along production and supply chains, including post-harvest losses, by 2030. Following the establishment of the aforementioned goal, Champions 12.3 was formed as a coalition of executives from governments, businesses, international organizations, research institutions, farmer groups and civil society with the objective of supporting the achievement of SDG Target 12.3.

Another important initiative is the World Food Preservation Center, which is formed of research universities located in North America, Hawaii, Asia, Europe, Africa, Australia and South America; two agricultural research institutes located in Israel and Morocco; and GrainPro, Inc., a major manufacturer of advanced postharvest technologies. Its aim is to "develop new sustainable technologies to combat food loss in developing countries and throughout the world". The global research organisation World Resources Institute (WRI) has 'food' as one of its six areas of work, where FW plays an important role.

4.2.2 European initiatives

There are a great number of initiatives in Europe tackling FW. The European Commission has an Expert Group on Food Losses and Food Waste whose aims include supporting the European Commission and the Member States in preventing and reducing FW. The European Commission also established an EU Platform on Food Losses and Food Waste to support the definition of measures needed to prevent FW, share best practice and evaluate progress made over time. FW is one of the issues the EU action plan for the circular economy is tackling (European Commision 2015).

Similarly, the European Commission Framework Programme 7 launched in 2012 the four-year project *Food Use for Social Innovation by Optimising Waste Prevention Strategies* (*FUSIONS*), which has produced reports of significant importance about FW quantities and standardised methods to assess FW in European countries. The joint declaration on FW *Every Crumb Counts* was launched in 2013 as an initiative that involves stakeholders from across Europe's FSC to reduce FW.

The European Commission is also working in the framework of the Lifelong Learning Programme in the two-year *FoRWaRd* project (*Food Recovery and Waste Reduction*), which aims to tackle FW through training and IT solutions. *REFRESH* (*Resource Efficient Food and dRink for the Entire Supply cHain*) is a research project funded by the Horizon 2020

Framework Programme of the European Union taking action against FW, which involves 26 partners from 12 European countries and China. *AgroCycle* is also a Horizon 2020 research and innovation project which addresses the recycling and valorisation of waste from the agri-food sector. It is led by the School of Biosystems and Food Engineering at University College Dublin, and involves 26 partners from 8 EU countries, two partners from mainland China, and one from Hong Kong.

4.2.3 Initiatives in the UK

The Waste & Resources Action Programme (WRAP), a charity organisation registered as a limited company, is the main body tackling FW in the UK. WRAP works with governments, businesses and communities to improve resource efficiency and move to a more sustainable economy. It launched the *Love Food, Hate Waste* campaign in 2007, which aims to raise awareness of consumer FW and to reduce it. WRAP also launched the *Courtauld Commitment*, a voluntary agreement funded by Westminster, Scottish, Welsh and Northern Ireland governments aimed at improving resource efficiency and reducing waste within the UK grocery sector. Four phases of the *Courtauld Commitment* have been consecutively launched:

1. *Courtauld Commitment 1* (2005-2009), which looked at new solutions and technologies to save food and primary packaging from becoming household waste.
2. *Courtauld Commitment 2* (2010-2012), which shared the same aim as *Courtauld Commitment 1* and extended it to include secondary and tertiary packaging, and supply chain waste.
3. *Courtauld Commitment 3* (2013-2015), which aimed at reducing FW in the food sector and to deliver sustainable growth, save money and reduce environmental impact.
4. *Courtauld Commitment 2025* (2015-2025), which aims to achieve a relative per capita reduction of 20% of FW, 20% in GHG intensity of food consumed and a non-specified reduction in impact associated with water use in the FSC. It is the *Courtauld Commitment* currently in force (WRAP n.d.).

Feedback is one of the most noticeable UK organisations that seek to reduce FW. It has launched the following initiatives so far:

1. The campaign *Feeding the 5000* raises awareness of the FW issue by organising events in large cities in which meals from food that otherwise would be wasted are prepared and served to 5000 people.

2. The *Gleaning Network* aims to save fresh fruit and vegetables on UK farms and direct this to people in need.
3. *The Pig Idea* promotes the practice of feeding pigs with FW and aims to lift the ban on feeding catering FW (FW from households or the food service) to pigs.
4. *Stop Dumping* draws attention to the food wasted in developing countries due to strict product specifications of European retailers.
5. *The Food Surplus Entrepreneurs Network* is a European community connecting food surplus entrepreneurs with organisations that are building solutions to FW.

One of the best ways to tackle FW is redistribution. FareShare, FoodCycle and Plan Zheroes are some of the organisations that help to collect surplus food and redistribute it to charities. Company Shop also collects surplus food, but sells it at a discounted price to Company Shop members. Company Shop has also launched the initiative *Community Shop* to help people at risk of food poverty. *The Real Junk Food Project* is a network of pay-as-you-feel cafes that serves food past its expiration date to the general public. It has opened cafes around the UK and has more recently expanded to other countries, such as France, Germany and Australia. In order to raise awareness of the FW problem, *This is Rubbish* aims to communicate the preventable scale of FW through policy research, community and arts led public events.

There are also examples of initiatives to support food businesses to manage or reduce their FW. *The Food Waste Network* helps businesses to find their best FW recycling options. *Working on Waste* is an initiative by the Institute of Grocery Distribution (IGD) to support food companies to help consumers to reduce FW. *Too Good To Waste*, launched by the Sustainable Restaurant Association, aims at increasing both consumer and industry awareness about the scale of restaurant FW and proposed ideas to reduce it (e.g. doggy bags). The Sustainable Restaurant Association has also launched the project *FoodSave*, which has helped almost 200 businesses in London between October 2013 and March 2015 to reduce their FW and manage surplus food and FW more responsibly.

In terms of research into valorisation options for FW, notable examples of projects and organisations include *WasteValor*, from the Green Chemistry Centre of Excellence at the University of York, which aims to create economic value from FW by offering scientific consultancy to waste producers and companies who could potentially use materials extracted from FW; *FoodWasteNet*, funded by the BBSRC and hosted by the University of Reading, a community of industrial practitioners and academic scientists that encourages the application of industrial biotechnology to FW to produce renewable chemicals and biomaterials with added value and market potential; and *Vision 2020*, launched by ReFood and aiming at banning the landfill of FW.

4.3 Food waste management solutions: the food waste hierarchy

There is a global consensus on the fact that prevention of FW generation is the optimal practice to deal with the FW issue, which therefore should be prioritised. Yet some FW will always be produced due to a number of reasons, including overproduction, damages to the food during manufacturing and human errors; and also because most raw materials in the food sector have associated inedible materials, namely food by-products. Although the most common management practice to deal with FW in the world is still landfilling (FAO 2013b), fortunately there are a number of alternatives which can provide value from FW. These alternative solutions for FWM can be classified according to their sustainability performance using the waste hierarchy, which is described in this section. The applicability of the waste hierarchy and waste management alternatives to deal with UK industrial FW is assessed and discussed.

4.3.1 Introduction and legislative framework

In 1975, the first Waste Framework Directive was launched to provide a legislative framework in order to protect human health and the environment against the adverse effects of waste (The Council of the European Communities 1975). It presented for the first time the concept of 'waste hierarchy', although without using that term. In 2008, the Directive 2008/98/EC was introduced, which contained a more detailed five-step waste hierarchy that must be applied by all Member States (The European Parliament and the Council of the European Union 2008). The waste hierarchy comprised, in order of preference, the following steps: prevention, reuse, recycling, recovery and disposal. It has proven to be a useful tool to rank waste management alternatives according to their sustainability performance. It has been continuously used since its introduction in 1975, not only in European Directives which have been implemented since then, but also by global organisations, such as the United Nations Environmental Program (UNEP 2011).

In the UK, the Government and institutions such as Defra et al. (2011) and WRAP (2011) have also used the waste hierarchy. In 2011 Defra published "Guidance on applying the waste hierarchy" based on the previous directives to help any business or public body manage their waste (Defra 2011c). Defra, together with WRAP and the Environment Agency, also produced the report "Applying the waste hierarchy: evidence summary", where scientific research on the environmental impacts of different waste management options was analysed for various products, including food (Defra et al. 2011). The waste hierarchy has also been implemented in UK law (Statutory Instruments 2011).

There is a considerable number of research papers published in prestigious scientific journals discussing the waste hierarchy, plenty of them focused on FW, e.g. Papargyropoulou et al. (2014), Eriksson et al. (2015). This proves the usefulness and acceptance of the waste hierarchy to classify and prioritise the most beneficial waste management solutions based on their sustainability performance (Papargyropoulou et al. 2014, Manfredi & Cristobal 2016). More detailed information on the technologies described in the waste hierarchy and their associated emissions can be found in the Best Available Techniques for the Waste Treatments Industries (European Commission 2006a).

Following the waste hierarchy, the most preferred management options when tackling FW are prevention of FW generation and reuse of the surplus food. Once the waste is created, the order of preference is recycling it into a second use, recovery treatment and disposal as the least preferred option. These five management possibilities are discussed in the following sub-sections and represented in Figure 4-1. The most common food waste management solutions (FWMSs) have been added and organised in line with the appropriate level of the waste hierarchy based on existing versions of the hierarchy and the author's knowledge. It is important to notice that the order of the FWMSs is debatable (e.g. considering thermal treatments with energy recovery more or less beneficial/damaging than landspreading). Indeed, the delimitation of the recycling and recovery options and which FWMS corresponds to which category is unclear at times (UNEP 2015); consequently they have been represented with the same colour in Figure 4-1. The specific food waste hierarchy (FWH) used in this research is presented and discussed in Section 7.5.1.

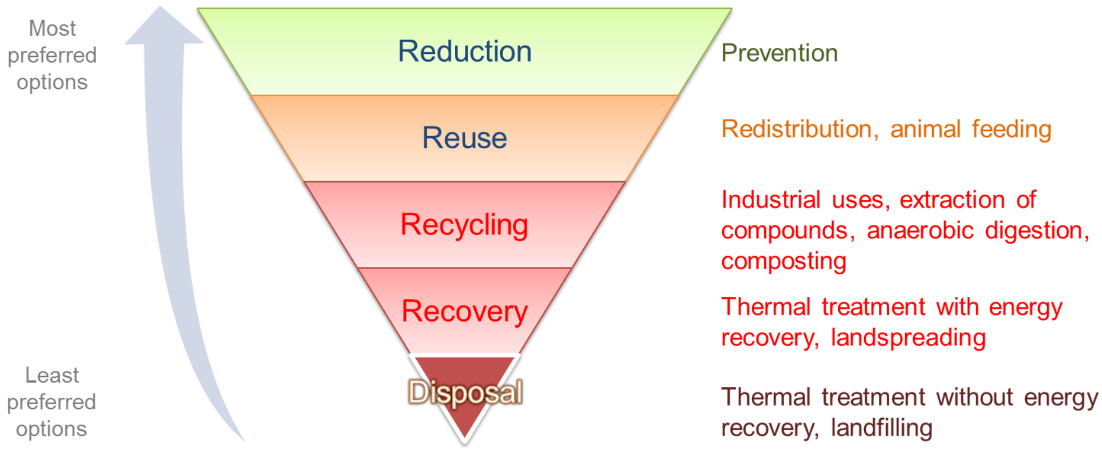


Figure 4-1. Food waste management solutions (FWMSs), arranged in the food waste hierarchy (FWH)

In addition to complying with the waste hierarchy, any company or person working with waste in England should fulfil the ‘Duty of Care’: classification of the waste; registration in case of production or storage of hazardous waste; obtaining a permit to store, treat, transport or dispose waste; storage of the waste safely and securely; following the rules for transporting waste and keeping a proof of license of other businesses that deal with waste and the aforementioned company or person (Gov.uk 2015a). Other regulations that may have to be complied with are the Hazardous Waste Regulations (Gov.uk 2014a), Nitrate Pollution Prevention Regulations 2015 (Gov.uk 2015b) and Animal By-product Regulations.

Other European regulations relevant to FWM were launched by the Commission of the European Communities (2008) and the European Commission (2010) on the management of bio-waste (which includes food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants), and The European Parliament and the Council of the European Union (2009a) on the management of animal waste and by-products.

More information about specific legislation regulating management of particular FW types can be found in Section 7.5.1.1.

4.3.2 Reduction

FW must be prevented at every stage of the FSC, particularly at the consumer level, where most UK FW is generated (Section 3.3.3). Nevertheless, this section describes prevention of FW during food manufacturing, as this is the stage on which this research focuses (as explained in Chapter 2). Prevention of FW can be applied to the edible parts of food surplus only, since there will always be inedible parts of food that will remain as FW. FoodDrinkEurope (2014) carried out a survey of 29 companies and associations within the FoodDrinkEurope membership and found that over 80% of respondents are working to identify the causes of their FW generation and optimising their production systems accordingly.

Ideally, the generation of FW should be avoided through appropriate management practices and control across the FSC up to retailers’ gate. IGD (n.d.) recommended six steps to prevent FW generation: measure it; engage people and raise awareness; design products, packaging and processes with waste-minimisation thinking; select a new product range to cut down waste; forecast demand precisely; and reshape processes to ensure products and information flows are seamless.

Some of the FW generated in the industry can be caused by other stages of the FSC, such as retailers. For instance, retailers' inaccurate forecasts may lead to overproduction from food manufacturers (Stuart 2009). In addition, retailers can often return food to manufacturers when it has not been sold and it is near its expiration date: in this way FW originally generated at retail level is moved to the manufacturing level (Stuart 2009).

An additional problem in the manufacturers-retailers interface is the short time that retailers give to manufacturers to react when they change their order. This issue can be improved through an extension of the order time or a reduction in the time the manufacturer needs to produce the food product. In order to comply with the second possibility, some food industries that produce different food products with a variety of ingredients (such as convenience foods) can develop and use standard processes which are common for all (or at least most) of their products (e.g. boiling rice), and then carry out the 'special operations' to give the different products their particular identity (e.g. adding sauces) (Darlington & Rahimifard 2006).

Other alternatives for prevention of FW generation include the usage of food products with aesthetical defects in a different manner than its original intended use. For instance, fruits with spots in their skin can be peeled and cut to be used in convenience foods. The industrial processes and their control must also be optimised for minimisation of FW (e.g. reduction of trimmings and minimisation of burning during cooking).

In addition to increasing resource efficiency of the processes and improving the management of the products and processes, an alternative product design can increase shelf life of foods and consequently reduce FW. Shelf life has been defined as "the estimated period during which the food maintains its safety and sensory qualities at a specific storage condition" (Joint FAO/WHO Food Standards Programme 2016). The shelf life of a food can be increased through an improvement in the design of the food product and/or its packaging. According to Defra & Food Standards Agency (2011), the shelf life of a food product is affected by the following factors: Good Manufacturing Practices, implementation of effective Hazard Analysis and Critical Control Points, quality of raw materials, processing steps, packaging, conditions of distribution, storage temperature, product formulation, and the intended use and target consumer.

4.3.3 Reuse

'Reuse', in this context, means that the product is used as a food product (i.e. consumed), although not with its original purpose, which is generally to be sold to the final consumer and subsequently consumed. This section describes the two possibilities to reuse surplus food: redistribution for human consumption and animal feeding.

4.3.3.1 Redistribution

When there is an unavoidable excess of food produced, the most recommended option is to redistribute it to feed humans. This includes reusing the food for charitable purposes, such as fundraising or raising-awareness events, or redistributing the food to people in need through food banks. There are a growing number of organisations which redistribute food in the UK, such as FareShare, Plan Zheroes and FoodCycle, as described in Section 4.2.3. Buksti et al. (2015) carried out a feasibility study to test how to set up an IT system in Denmark that connects organisations with surplus food like supermarkets with local organisations such as homeless shelters, which can be useful to implement a redistribution programme. Bilska et al. (2016) identified the following defective products as appropriate for redistribution, since they do not pose a threat to human health: wrong labelling of packages, food product wrong weight, close-to-end expiration date and mechanical damage to bulk packages.

In the UK, the Government does not provide direct support to food banks (Downing et al. 2014). O'Connor et al. (2014) carried out a comprehensive study on current legislation and practices concerning food donation in European countries, and recommends a clarification around VAT liability on donated food and EU guidelines for assessing additional lifetime of products. A more detailed analysis of food products suitable for redistribution can be found in Section 7.5.1.1.

Redistribution must be prioritised for avoidable FW that could not be prevented. It can provide not only a clear social benefit, but also an economic benefit to the donor (Giuseppe et al. 2014). On the other hand, Reynolds et al. (2015) assessed economic and environmental consequences of redistributing food to people in need in Australia, and found that this option can be more economically costly than other options lower down in the FWH.

4.3.3.2 Animal feeding

When redistribution of food to people is not possible, it should be distributed for animal feeding. However, since 2001 in the UK and 2002 in the EU feeding farmed animals with catering FW is forbidden (Defra n.d., Gov.uk 2014c). In addition, preparation of animal feed from FW that has been in contact with animal by-products is significantly restricted, and the following legislation must be followed: European regulations (European Commission 2005a, The European Parliament and the Council of the European Union 2009a, European Commission 2011) and UK legislation (The Secretary of State 2013). A more detailed assessment of the types of FW fit for animal feeding can be found in Section 7.5.1.2.

Parfitt et al. (2016) provides useful guidance on the use of FW as animal feed for food manufacturers and retailers, recommending dry carbohydrate rich foods such as cereals and bread to feed animals. San Martin et al. (2015) produced animal feeds from vegetable waste using drying techniques such as pulse combustion drying, oven and microwave, concluding that vegetable waste is both nutritionally and sanitarily appropriate for use in animal feeds. Chen et al. (2015) claimed that FW treated with fermentation, heat treatment or coupled hydrothermal treatment and fermentation produces nutritional and valuable animal feed, although the presence of bovine- and sheep-derived materials and a few chemical contaminants such as Pb were close to or might exceed the legislation permitted values in animal feeding. However, conclusions by Chen et al. (2015) might be China-specific, and different results could be achieved, particularly in terms of contaminants present in animal feeds, in other regions of the world with different food systems and regulations. In the UK, *The Pig Idea*, a campaign by the organisation Feedback, promotes the use of FW to feed pigs and aims to lift the ban on feeding catering FW to pigs. The use of FW as feed is applicable to some types of avoidable, possibly avoidable and unavoidable FW.

The intensive animal farming practices increasingly used over the last decades have switched livestock diets from grass and FW to grains and imported proteins like soya. However, animal feeding as an alternative for FWM is economically advantageous, since FW can be typically sold to produce animal feeding at prices ranging from £30 to £50 per tonne (Parfitt, Stanley, et al. 2016). This option is also environmentally friendly: Stuart (2009) argues that at least 20 times more CO_2 is saved by feeding pigs with FW rather than using it for anaerobic digestion. Salemdeeb et al. (2017) also demonstrated that reusing dry or wet FW as pig feed has lower environmental impact than AD or composting.

4.3.4 Recycling

If the surplus food cannot be redistributed, altering it to obtain an alternative application is the most recommended option. This includes extraction of compounds of interest from FW and industrial uses, anaerobic digestion, and composting.

4.3.4.1 Extraction of compounds and industrial uses

There are a significant number of valuable compounds in FW that can be extracted and used within different applications (Ravindran & Jaiswal 2015). This can play a pivotal role in a sustainable biobased economy, due to their high volume, chemical richness and heterogeneity (Matharu et al. 2016). Some of the extraction processes require complex technology and are expensive; additionally some technologies are not fully developed and need to be scaled up, which brings additional challenges (Galanakis et al. 2015, Matharu et al. 2016). A lack of industry expertise and experienced workforce, along with the heterogeneity and seasonal production of FW are also relevant problems in obtaining valuable compounds from FW (Lin et al. 2014). Therefore, FW from the early stages of the FSC (such as industrial FW) is more suitable for compounds extraction and industrial applications since they are more homogeneous and their supply is more stable than that of consumer FW (Girotto et al. 2015). In all circumstances, after extracting compounds from FW there is a residue to treat, i.e. a leftover FW.

Galanakis (2015) presented a 5-Stage Universal Recovery Process applicable to extraction of compounds from FW, which includes the following stages: macroscopic pretreatment, macro- and micro-molecules separation, extraction, isolation and purification, and product formation. Waldron (2007) provided an extensive review of technologies and processes needed to extract useful compounds from FW. Fat can be separated from animal by-products in rendering plants and be used to produce animal feeds, fuel, soap and other products (Meeker 2006). Essential oils, aromas and colourings can also be extracted from vegetables and fruits (Morawicki 2012). Substances can be extracted from citrus waste and wheat bran to be used as ingredients in new foods (Fava et al. 2013). Okoro et al. (2016) reviewed processes to obtain compounds from meat processing waste, classifying them into thermochemical, biochemical and physicochemical technologies, and identified the following challenges to undertaking those processes: technical difficulties, economic performance, heterogeneous FW composition and onsite integration challenges. Pleissner et al. (2016) extracted succinic acid, lactic acid and fatty acid-based plasticiser from agricultural residues and FWs. Gould et al. (2016) used materials prepared from FW as emulsifiers. Mirabella et al. (2014) compiled a list of substances that can be extracted from different FWs and reviewed their uses, concluding that research mainly focuses on the extraction of antioxidants, fibre, phenols, polyphenols and carotenoids, because of their potential to be used in a range of applications. Galanakis (2012) classified substances according to their FW source, reviewed established and emerging technologies needed to carry out the extraction processes and discussed issues related to safety and cost of the processes and commercialisation of the products obtained.

Considerable potential also exits to use FW to produce biofuels (e.g. biodiesel and bioethanol), supporting the transition from a fossil fuel-based economy to a sustainable, circular economy based on renewable energy sources (Zhang et al. 2016, Skeer & Nakada 2016, Karmee 2016).

Other industrial applications of FW include adsorption of heavy metals from aqueous solutions (Arvanitoyannis et al. 2006), production of construction bricks (Aliyu & Bala 2013) and its use as adsorbents for carbon dioxide and benzene gas sorption (Opatokun et al. 2017).

4.3.4.2 Anaerobic digestion

Anaerobic digestion (AD) is a process in which organic matter is broken down by bacteria in the absence of air, producing a gas, namely biogas, and a residue, namely digestate. The AD process is divided into the following steps: hydrolysis of the organic matter, conversion of decomposed matter to organic acids and reaction of the acids to obtain biogas (Arvanitoyannis et al. 2008). The remaining digestate from the digestion can be used as a fertilizer (Tampio et al. 2016), following specifications by British Standards Institution (2014).

The biogas is composed of an approximate proportion of 48-65% methane, 36-41% carbon dioxide, with a minor proportion of other gases: nitrogen (up to 17%), oxygen (<1%), hydrogen sulphide (32–169 ppm) and traces of other gases (Khalid et al. 2011). The biogas is generally used to generate heat and/or electricity (Whiting & Azapagic 2014), although it can also be directed into the gas grid or used to produce fuels for vehicles (Grosso et al. 2012). In the UK, nearly all biogas produced until 2014 was used to fuel combined heat and power engines (Styles et al. 2016). The UK Government has supported the AD sector over the last years with subsidies such as the Renewable Heat Incentive, which provides financial support to renewable heat technologies, and the Feed-in Tariff, which supports the generation of low-carbon electricity using small-scale systems (Gov.uk 2008), although there are concerns that such subsidies have been already lowered and could disappear in the future (ADBA 2016b). Additionally, gate fees are paid by waste generators and bring additional income to the AD operator. The median AD gate fee for food waste is currently £40/tonne (Hannah Dick et al. 2016).

The AD sector has grown rapidly over the last years. In the period 2014-2015, over 100 AD plants were commissioned per year, reaching a total of 540 AD plants in December 2016 (ADBA 2016a). ADBA (2017) mapped all AD plants in the UK, which can be classified into their different main uses (electricity, biomethane to grid or heat) and feedstock used (agricultural, industrial, municipal/commercial or sewage sludge). Currently, most of the AD plants produce electricity and are fed with agricultural products, which include FW. In 2015, over 90 AD plants exclusively treated FW (Morton 2015). At the end of 2014, the headline capacity of operational source segregated FW AD plants was claimed to be 2.6 2.6 Mt per year, which is an increase of 1.2 Mt per year from 2012 (UK Green Investment Bank 2015).

FWs are an ideal substrate for AD due to their high moisture content and easy biodegradability (Mao et al. 2015, Sen et al. 2016). Alternatively, FW can be used as a co-substrate together with other substrates, improving biogas production (Chiu & Lo 2016). Generally, AD is considered more environmentally friendly than composting (Defra 2011b, Defra et al. 2011, Fisher et al. 2013). Additional information on suitable FW for anaerobic digestion can be found in Section 7.5.1.3.

4.3.4.3 Composting

Composting is a process in which microorganisms transform organic waste into a nutrient-rich soil conditioner called compost. Unlike anaerobic digestion, the metabolism of these microorganisms uses oxygen. Composting can be carried out in vessels at an industrial level and at households. In-vessel composting is currently carried out in containers, silos, agitated bays, tunnels and enclosed halls (IGD n.d.). In-vessel composting is the only legal method to compost commercial FW that has been in contact with animal products (WRAP 2011). Alternative methods to in-vessel composting are static piles, static piles with forced aeration, windrow composting, passively aerated windrows and vermicomposting (Cooperband 2002).

Composting as a waste management solution shows clear advantages: it is cheap to undertake and eliminates the payment of tipping fees, it produces a product that can generate revenue, and it can reduce the volume of waste by up to 40%, whilst killing most pathogens during the thermophilic phase (Schaub & Leonard 1996).

Li et al. (2015) identified the starting culture, i.e. the type of material that starts the composting process, as the most critical factor contributing to product maturity, i.e. the efficiency of the compost process, followed by the aeration rate. In order to achieve an optimal composition of feedstock, several raw materials may be needed (Cooperband 2002). Numerous materials, namely bulking agents, can be mixed with FW to increase the efficiency of the composting process, including wood chips, wheat straw, sawdust, rice husk, rice bran, chopped hay, wood shavings and peanut shells (Chang & Chen 2010). Additional information on suitable FW for anaerobic digestion can be found in Section 7.5.1.4.

A Quality Protocol has been developed by WRAP (n.d.) to set out criteria for the production and use of compost. WRAP has also published good practice guidance for farmers, growers, advisers and agricultural contractors to carry out the composting process successfully (WRAP 2016). The compost produced must meet specifications by the British Standards Institution (2011).

4.3.5 Recovery

When FW cannot be recycled, it should be used in a way that maximises the value recovered from it. The two most significant options to recover value from FW are thermal processes with energy recovery and landspreading.

4.3.5.1 Thermal treatments with energy recovery

Thermal treatments with energy recovery include different processes such as incineration, pyrolysis and gasification, which differ mainly in the temperatures reached and the materials obtained (Arvanitoyannis et al. 2008). These waste treatments are carried out in order to recover energy in the form of heat and/or electricity (Kwak et al. 2006). The bottom ash (i.e. the remaining solid after thermal treatment) and residues found in air pollution control devices may also be valuable in further industrial applications (Ahmed & Gupta 2010, Brunner & Rechberger 2014). A reference document on the Best Available Techniques for Waste Incineration has been prepared by the European Commission, which focuses on incineration but also covers pyrolysis and gasification processes (European Commission 2006c).

During incineration, the waste is burnt at 870-1200 ºC so the solids and liquids convert into gases. The gases obtained are further heated and broken down into simple molecules and reacted with oxygen. At the end of the process, the gases produced include carbon dioxide, water, carbon monoxide, nitrogen oxides and other compounds; the remaining solid is ash and slag (Arvanitoyannis et al. 2008).

Pyrolysis is a similar process that usually occurs under pressure, at temperatures above 430 ºC and with no oxygen. The main gases released are carbon monoxide, hydrogen, methane and other hydrocarbons; also a small quantity of liquid and coke (solid residue) is obtained (Arvanitoyannis et al. 2008).

In the case of gasification, the gas obtained, namely syngas, consists mainly of carbon monoxide and hydrogen. The solid residues are ash and char. The temperatures reached are normally higher than 700 ºC and a controlled amount of oxygen and steam is used during the reaction (Arvanitoyannis et al. 2008). Gasification has proven to be more beneficial than pyrolysis, although a longer period of time was needed to finish the gasification process (Ahmed & Gupta 2010).

In the case of FW, in addition to the processes described above, hydrothermal carbonisation is a thermal treatment which is attracting increased attention from researchers, since it is especially advantageous for treating waste with high moisture, and produces a highly energy densified material (hydrochar) (Pham et al. 2014). Thermal treatments can be potentially applied to every FW type, although they are more economically beneficial when treating dry FWs.

Although these processes are less efficient than coal-fired power stations and generate ashes and noxious pollutants to human health that also have a negative effect on water, soil and air (FAO 2013b), they replace the combustion of fossil fuels, and FW can be considered a renewable material. It also significantly reduces the volume of waste and destroys potentially harmful substances, including pathogenic microorganisms and viruses (Brunner & Rechberger 2014). On the other hand, it creates environmental impacts, mostly due to gas emissions, and also social impacts such as odour, noise, dust and traffic (Defra 2013b). It is also a costly method, due to high capital and maintenance costs (Thi et al. 2015).

Caton et al. (2010) claimed that energy recovery from thermal treatments of FW could result in cost savings by offsetting the use of traditional fuels (e.g. natural gas for heating) and by reducing disposal costs, although FW is not appropriate for thermal treatments due to its high water content. Different thermal treatments are frequently carried out consecutively, for instance pyrolysis in a first stage and gasification in a second stage (Ahmed & Gupta 2010), and they can also be combined with other FWMSs, for example pyrolysis can be used to treat digestate resulting from AD (Opatokun et al. 2015).

After sending the waste to landfill and open dumping, thermal treatments (with and without energy recovery) are the most common method to deal with waste worldwide (Arvanitoyannis et al. 2008). In EU-15, around 20-25% of the total 200 Mt of municipal solid waste (MSW) produced in 2006 was treated by incineration (European Commission 2006c).

In England, 15.1% of the total MSW produced in 2010-11 was treated by incineration. It is important to notice that in high-income countries the organic fraction of MSW is over one third, of which FW represents a large proportion (UNEP 2015).

4.3.5.2 Landspreading

Landspreading consists of spreading an organic material, usually a waste, onto the land in order to increase the nutrient content of the soil. Landspreading of FW can enhance physical, chemical and biological characteristics of the soil, reducing the need for manufactured fertilisers to support plant growth (Environment Agency 2013).

At the farm stage, landspreading can be a good management option because farmers can spread FW, typically inedible parts of harvested plant-based products, onto their soil, and therefore FW does not have to be stored and transported. If animal-based material is used, the proximity of a groundwater source must be checked, since faecal bacteria, *Cryptosporidium* and viruses, amongst other microorganisms, can be present in animal waste and therefore contaminate water (Environmental Protection Agency 2004). The amount of sand, silt and clay in the soil (which defines its texture) must be determined in order to landspread, along with the organic matter content, depth and underlying geological parent material in the soil (Environment Agency 2013). In August 2016, the Environment Agency published its response to a consultation calling for views on proposed changes to a number of standard rules for the Environmental Permitting Regulations in relation to landspreading, which is yet unpublished on Gov.uk (Environment Agency 2016).

Marsland & Whiteley (2015) published a Rapid Evidence Assessment methodology to identify key hazards which can arise during or after landspreading a specific waste on agricultural land. The Food Safety Authority of Ireland (2008) analysed the most relevant hazards for landspreading of agricultural, municipal and industrial materials on agricultural land used for food production, and divided them into the following two categories:

1. Microbiological hazards: viruses, bacteria, parasites (such as protozoa and helminths) and Transmissible Spongiform Encephalopathies (caused by prions).
2. Chemical hazards: metals (such as nickel and selenium), organic pollutants (such as PAHs, dioxins and PCBs), disinfectants and detergents, musk compounds, medicines and illicit drugs (including veterinary and human medicinal products such as antibiotics), endotoxins and Endocrine Disrupting Substances (such as phthalates and some pharmaceutical compounds).

On the other hand, certain FWs such as agricultural by-products can be used as amendments in the remediation of soils contaminated with trace metals and metalloids (Clemente et al. 2015). Gendebien et al. (2001) estimated that over 90% of the waste spread on land in EU-15 in 2001 was farm waste, primarily animal manure. Of the remainder, the most important waste categories are food production wastes, dredgings from waterways and paper waste sludge.

4.3.6 Disposal

Disposal of FW is the last option in the FWH, which should always be avoided. It includes thermal treatment without energy recovery and landfilling.

4.3.6.1 Thermal treatment without energy recovery

Thermal treatments without energy recovery are similar to those described in Section 4.3.5.1, but without a recovery of energy from the waste treatment. It essentially consists of burning the waste, often in open air. The solid residue, namely char, can be recovered and used in a range of industrial and domestic applications, including as a fuel (charcoal) and as a soil amendment (biochar) (Lohri et al. 2015). Additionally, the waste volume is reduced and harmful substances are destroyed (Brunner & Rechberger 2014). However, the heat is lost and the gases obtained in the process are toxic and increase the greenhouse effect. Because of the lack of benefits and the severe air pollution caused during the process, thermal treatments without energy recovery are discouraged (Hoornweg & Bhada-Tata 2012).

This management option is more commonly used in developing areas of the world, since its practice is strictly regulated in developed countries (Guendehou et al. 2006). FW is typically mixed with other consumer waste in MSW when processed with thermal treatments without energy recovery (Caton et al. 2010).

4.3.6.2 Landfilling

A landfill is a waste disposal site for the deposit of waste onto or into land (Environment Agency 2010). Therefore, regardless of whether landfilled waste is buried or not, landfilling has a significant environmental impact and minimal positive effects. Microorganisms decompose the organic matter, generating principally methane and carbon dioxide, gases which significantly increase the greenhouse effect. On the other hand, gases emitted can be collected and used to produce energy in properly managed landfills (Emkes et al. 2015).

Other toxic compounds generated in the process can contaminate the atmosphere, water and land, spreading diseases that can affect humans (FAO 2013b).

The European Council Directive 1999/31/EC regulates operational and technical requirements of landfilling to minimise negative effects on the environment (The Council of the European Union 1999). BiPRO (2008) prepared a report for the European Commission with the conclusions of a series of workshops involving the Member State authorities and the Commission Services on raising awareness concerning the application and enforcement of community legislation on landfills. In the UK, Defra published the Environmental Permitting Guidance (Defra 2010) to support those regulating and operating landfill sites to comply with European regulations. Following the aforementioned European Directive, the UK approved the Waste and Emission Trading Act in 2003 (Legislation.gov.uk 2003) and launched the Landfill Allowance Trading Scheme (LATS) in 2004 (Defra 2012), which restricted the amount of municipal bio-waste sent to landfills. The importance of LATS diminished after 2008, mostly because the introduction of the landfill tax, which has been considered more effective at discouraging landfill use (Defra 2012, Hill 2014). Ultimately, LATS was suppressed in September 2013 (Calaf-Forn et al. 2014). There are two rates of landfill tax: a standard rate for active wastes such as household waste which decays, and a lower rate for less-polluting waste (HM Revenue & Customs 2014). Currently, the standard rate is £84.40 per tonne, and the lower rate is £2.65 per tonne (Gov.uk n.d.). Because of these regulations, and increasing environmental awareness, a large number of UK companies have targeted towards a "Zero waste to landfill" strategy.

From 1996-97 to 2012-13, the proportion of waste landfilled in England decreased progressively year-on-year, from 1996 to 2006 due to an increase in recycling and since 2005-06 due to an increase in recycling and incineration (Farmer et al. 2015). Globally, landfilling is still the most common solution to manage FW (FAO 2013b).

Landfilling is the last option in the waste hierarchy, which should always be avoided due to significant environmental consequences and a lack of socio-economic benefits. Yet, landfilling waste in a properly controlled landfill site is recommended against options such as fly-tipping and open dumping, which are illegal in most developed countries. In the UK, where this practice is illegal, there were 900,000 incidents of fly-tipping in 2014-15, which caused an economic cost to the local authorities of £50 million (Defra & Government Statistical Service 2015). On the other hand, disposing of FW into the sewer is generally considered as negative as landfilling, and many references place it at the same level of the

FWH as landfilling (e.g. WRAP (2017)). Nevertheless, this option is not included in the FWH (Figure 4-1) because it is not considered a FWMS.

4.3.7 Applicability of the food waste hierarchy

The waste hierarchy applied to FW, presented in Figure 4-1, is useful in distinguishing amongst different options to manage FW according to their socio-economic benefits and environmental impacts. However, not every type of FW is suitable for following all the FWMSs discussed. There are restrictions based on regulations and laws: some treatments for some types of FW are not permitted, as per EU and UK legislation. A few examples of such banned treatments for some FW types can be seen in Table 4-1.

Consequently, an identification of all types of FW seems to be necessary in order to understand which FWMS is suitable for each FWM situation. Next, a targeted analysis of each FW type identified is necessary to cast FWMSs aside when they are not permitted. Therefore, the applicability of the FWH is limited, since not all FWMSs are suitable for all FW types. Furthermore, some FWMSs, such as extraction of compounds of interest and industrial uses, are entirely different for each FW type, in terms of the processes needed and the outputs generated.

Unfortunately, the FWMSs at the top of the FWH are applicable to fewer FW types than those at the bottom. Consequently, a range of different solutions is required for a tailored treatment of each FW type. For example, the reduction in the previously widespread use of FW for animal feeding due to a stricter regulation has resulted in fewer types of FW that can be used to feed animals (Defra n.d.). Health and safety concerns influence legislation on FWM, and governments must protect the health and wellbeing of their citizens. However, bans of FWMSs also result in the unintended consequence that less-advantageous FWMSs are utilised more often. With regard to the animal feeding example, there are initiatives to

Table 4-1. Examples of FW types that cannot be managed following some FWMSs

Banned FWMS	FW type	Regulation
Redistribution	Spoilt	The European Parliament and the Council of the European Union (2002)
Animal feeding	Catering	Gov.uk (2014c)
Animal feeding	Some animal by-products	European Commission (2011)
Windrow composting	Commercial FW that has been in contact with animal products	WRAP (2011)
Composting	Some animal by-products	The European Parliament and the Council of the European Union (2009a)

change legislation and allow more types of FW to be fed to animals (Stuart et al. n.d., Salemdeeb et al. 2017).

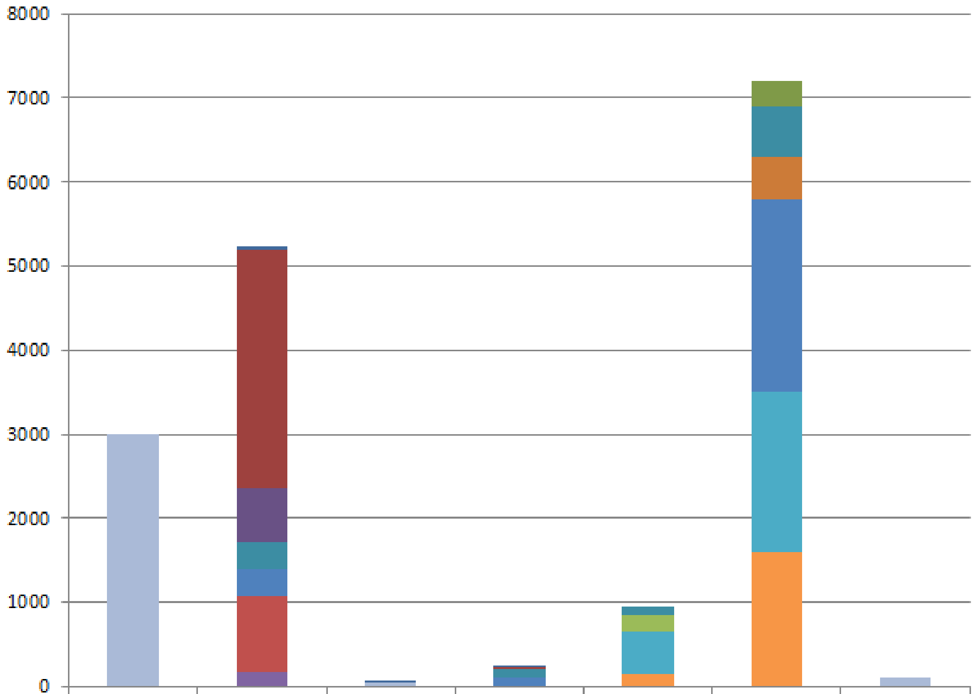
Additionally, it is difficult to apply a waste hierarchy to food products due to the heterogeneity of these materials and the number and types of actors at different levels of the FSC that generate FW. Therefore, ideally the FWH should be assessed for each type of FW, rather than for 'food waste' as a whole, creating a FWH for each FW type identified. This would allow a targeted analysis of all FWM possibilities under a specific scenario, ensuring the most sustainable FWMS is followed in all cases. This case-specific application of the waste hierarchy has also been recommended by Rossi et al. (2015) in their analysis of the applicability of the waste hierarchy for dry biodegradable packaging. Defra (2007); Laurent, Bakas, et al. (2014) and Eriksson & Spångberg (2017) also noted that the waste hierarchy is useful as general guidance but exceptions for particular materials and circumstances may occur.

In line with the conclusion presented in this section, a review of existing categorisations of FW, along with methodologies to identify sustainable solutions to manage them, is presented in Chapter 5. The issue identified in this section is further discussed and assessed in Chapter 7, in which a systematic approach is used to identify FW types and suitable FWMSs to treat them.

4.4 Quantification of food waste management solutions in the UK food supply chain

As described in Section 4.3, there are a number of solutions to manage FW. All these options are currently used in the UK, but in very different proportions, varying across the different levels of the FSC. Figure 4-2 shows the quantity of FW treated with each of the FWMSs from the FWH, divided into the different stages of the UK FSC. Data has been collected from the following references at each stage of the FSC: manufacture: Parfitt et al. (WRAP) (2016); wholesale: Parfitt & Parry (WRAP) (2016) and Parfitt (WRAP) (2016); retail: Parfitt (WRAP) (2016); food service: Oakdene Hollins et al. (WRAP) (2013) and WRAP (2017); and household: Defra (2015), Quested & Parry (WRAP) (2017) and WRAP (2017). It must be noted that FW from manufacture amounts to a higher quantity than that reported in Figure 3-7, since WRAP does not include some food by-products in its FW definition, as explained in Section 3.3.3. On the other hand, other sources, such as the Foodchain and Biomass Renewables Association (Fabra UK), estimated a higher quantity of FW going to industrial uses, particularly animal by-products sent to rendering. According to Fabra UK, this could be as high as 2.25 Mt per year, although WRAP considers this an over-estimate (Parfitt, Woodham, et al. 2016). Additionally, the total sum of FW from each stage of the FSC can be slightly different than that reported in Figure 3-7 due to rounding.

As can be seen in Figure 4-2, it can be assumed that the sustainability of the FWMSs used in the food service and household stages is lower than that of manufacturers' FW, based on the FWH. This can be explained because at the end of the FSC, particularly at the household level, FW is often mixed with other materials, forming a heterogeneous waste which is difficult to manage and obtain value from it. Therefore, sustainable FWMSs such as redistribution, animal feeding and industrial uses are not applicable for these types of FW, e.g. domestic FW contaminated with other materials.



	Production	Manufacture	Wholesale	Retail	Food service	Household	Others
Redistribution		37	5.3	5			
Animal feeding		2835	0.03	27			
Fed to pets						300	
Industrial uses (e.g. rendering)		635	0.225				
AD/composting		337		105	107	600	
Home composted						500	
Thermal treatment		307		105		2300	
Landspreading		905					
Thermal treat./landspreading					200		
Other treatment		171					
Landfill		2			510	1900	
Sewer					143	1600	
Unknown	3000		37				104

Figure 4-2. Use of different FWMSs across the UK FSC according to WRAP and Defra data, in kt

On the other hand, manufacturers generally manage their FW more sustainably, sending a significant amount to animal feeding. Manufacturers commonly have more capability than consumers to find the best solutions to increase efficiency in their activities, which partially explains why manufacturers tend to manage their FW more sustainably than consumers. Additionally, homogeneity of manufacturers' FW makes it significantly easier to use a wider range of solutions for FWM. Manufacturers also segregate their FWs into different categories which can be managed differently according to their characteristics, as opposed to consumers.

Nevertheless, manufacturers often manage their FW in unsustainable ways. Solutions such as thermal treatments and landspreading are still commonly used, whilst the most sustainable FWMS according to the FWH, i.e. redistribution for human consumption, is barely used. This means that opportunities to increase the sustainability of FWM practices at the manufacturing level exist. As manufacturers are the second largest FW generator in the UK FSC, finding ways to manage their FW more sustainably will presumably generate a significant, positive effect in the UK, in terms of not only minimising environmental impacts, but also creating socio-economic benefits.

4.5 Chapter summary

This chapter has described the most significant initiatives to tackle the FW issue in the world, Europe and the UK. Most efforts have been directed towards a minimisation of FW, rather than an optimisation of FWM. Next, the FWH has been presented and all of its FWMSs have been described. The FWH has also been critically analysed to find shortcomings in its applicability. Consequently, a thorough study of FW types and characteristics has been proposed to identify the FWMSs with the most potential to improve the sustainability of a FWM.

The usage of different FWMSs from the FWH in the UK FSC has been shown and analysed, concluding that optimising manufacturers' FWM is a valuable opportunity to improve the sustainability of the UK food systems. The reasons as to why increasing the sustainability of UK manufacturers' FWM can be significantly beneficial, and consequently the justification of the scope of this research presented in Section 2.5, is summarised in the list below:

1. Manufacturers generate the second largest quantity of FW in the UK FSC.
2. A large proportion of manufacturers' FW is unavoidable and cannot be prevented.
3. Manufacturers often manage their FW in unsustainable ways, e.g. thermal treatments.

4. Manufacturers' FW is homogeneous and its composition and quality is generally known, thus more FWMSs are suitable for use and results from their implementation are more easily assessable.
5. Manufacturers tend to segregate their waste into different categories, or at least they could easily start to do so, thus more FWMSs are suitable for use and results from their implementation are more easily assessable.
6. FW generates an economic loss to manufacturers, thus they will presumably be receptive to finding ways to improve their FWM if this causes an economic benefit.
7. Manufacturers generally have capacity to implement changes to optimise their performance.

Whilst this chapter has reviewed the most significant options to manage FW, Chapter 5 reviews categorisations and methodologies that can be useful to identify the most sustainable option to manage FW in the industry.

CHAPTER 5 A REVIEW OF CATEGORISATIONS AND METHODOLOGIES FOR FOOD WASTE MANAGEMENT

5.1 Introduction

The initial section of this chapter reviews and discusses existing categorisations of FW. The second section of the chapter evaluates methodologies and tools to assess waste management systems, and their applicability to FWM systems. An analysis of the strengths and weaknesses of these methodologies is used to identify research gaps that the research reported in this thesis aims to fill. This analysis is also used to justify the need of this research and to precisely define the research scope presented in Chapter 2.

5.2 Categorisations of food waste

FWs are heterogeneous materials which significantly differ from each other. It is readily seen that there is a number of types of FW, with significant differences between them, e.g. in terms of their chemical composition and nutrient content. These differences produce distinct properties for each FW type, which presumably means that some FWMSs may be more suitable and beneficial for some FW types than for others. As explained in Section 4.3.7, a better understanding of the FW characteristics makes it easier to select the FWMS that optimises the results obtained from FWM. This section reviews existing FW categorisations and critically analyses their applicability and usefulness for identifying the most sustainable FWMS. FW categorisations should consider all the divisions necessary to link the FW under consideration with a FWMS in a way that their socio-economic benefit is optimised and their environmental impact is reduced to its minimum level.

Generally, each study that deals with the FW issue uses its own categorisation of FW (Lebersorger & Schneider 2011). This causes a lack of homogeneity amongst the different studies, not only on FW definitions and categorisations, but also in assessments of ramifications generated from FWM. A unified terminology is needed so results from different studies are comparable.

5.2.1 European regulations

The Commission Decision 2000/532/EC aimed at providing a common terminology for Member States in order to improve the efficiency of waste management practices (European Commission 2000). It includes a European List of Waste that encodes types of waste according to their characteristics. This list is particularly useful to categorise hazardous wastes. However, although it includes a category for wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing, the food categories used are too general. The European List of Waste is complemented by Directive 2008/98/EC (The European Parliament and the Council of the European Union 2008), which also classifies hazardous wastes, in this case by its hazard type, e.g. explosive, oxidising, flammable or irritant. These regulations were assessed by Sander et al. (2008) on behalf of the European Commission, with the aim of simplifying and updating the aforementioned legislation.

The European Commission also proposed a standard characterisation method for municipal solid waste (European Commission SWA-Tool Consortium 2004). These classifications include all types of waste, and therefore it is too general to be used for categorising FW in sufficient detail to identify optimal FWM opportunities. Consequently, a tailored categorisation process specific for food systems is necessary.

Furthermore, the European Directive 2006/12/EC, which was repealed in 2010, classified waste into 16 categories, including according to the reason for disposal, damages in the product, end of its service life and the original use of the product (European Parliament 2006). This classification criterion may be useful to understand why waste was generated, but not particularly beneficial to decide how to manage it.

5.2.2 Categorisations of FW by food type

Narrowing down the scope of waste categorisations, the simplest FW categorisation classifies FWs according to food types, e.g. cereals, fruits, meat, fish and drinks. This classification is widely used and is useful to quantify the amount of FW based on mass, energy content and economic cost. Bernstad Saraiva Schott & Cánovas (2015) analysed avoidable FW types based on their associated environmental impact, recommending classifying FW in the following categories: vegetables/fruit, bread, cheese, other dairy products, fish, meat (beef) and meat (other than beef). As Bernstad Saraiva Schott & Cánovas (2015) notes, this categorisation does not cover all FW types, e.g. spices, oils, most drinks, snacks and sweets.

Zheng et al. (2013) assessed the methane yield potential of several FW types, which is useful to model anaerobic digestion and landfilling operations. They concluded that FW should be classified into animal-derived and plant-derived FW, and plant-derived FW should be further subdivided into nut FW and non-nut FW.

Figure 5-1 shows an example in which domestic avoidable FW is categorised according to high-level food types, and the proportion of each FW category represents its proportion of weight or cost over the total. There are many other sources that categorises FW according to its food type, e.g. Flores et al. (1999), Malamis et al. (2015). Venkat (2011) used a comprehensive bottom-up approach in which 134 food products were analysed and then classified into 16 major categories.

FW categorisations by food type are typically based on codes. The Food Loss + Waste Protocol (2016) published a Food Loss and Waste Accounting and Reporting Standard (FLW Standard) that recommends the use of the Codex Alimentarius General Standard for Food Additives (GSFA) system or the United Nations' Central Product Classification (CPC) system as main codes, and when more precise classifications are needed, the Global Product Category (GPC) code or the United Nations Standard Products and Services Code (UNSPSC) as additional codes. These codes are described in the next page.

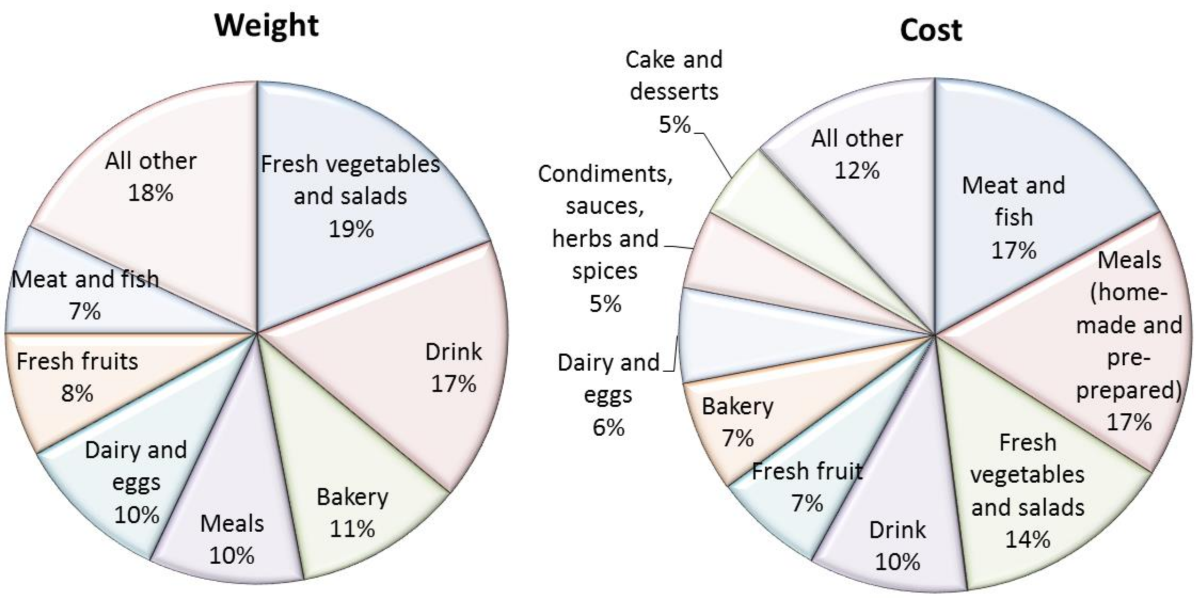


Figure 5-1. Proportions of avoidable FW in households in 2012 by weight and cost. Adapted from Quested et al. (WRAP) (2013) ®WRAP

- The GSFA (WHO & FAO 2016) code provides a comprehensive list of 16 food categories along with a description of the foods in each category. It was designed to describe admissible food additives for various food categories.
- The CPC (United Nations Statistics Division 2015) is not focused exclusively on the food sector. In comparison to the GSFA system, its categorisation of some food types is more detailed, providing more classification options.
- The GPC (GS1, GPC n.d.) provides detailed classification attributes for products, however it focuses on retail trade.
- The UNSPSC (GS1, UNSPC n.d.) provides a global classification framework for all products and services in all industry sectors.

The GPC and UNSPC systems complement each other and do not overlap, and in the same time both allow a more detailed FW categorisation than those by GSFA and CPC.

However, according to the FLW Standard, in some occasions these four classifications may not provide enough detail of food types, e.g. for items that are composed of multiple ingredients (e.g. ready meals), and this reduces the applicability of these codes. In this type of cases, the FLW Standard recommends to describe such food product with a commonly-used name that would be understood by those managing FW, although this lack of detail would affect the selection of the FWMS.

The FLW Standard also distinguishes between 'food category' and 'material type'. 'Food category' alludes to the types of food included in the FW being reported, and refers to the classifications based on the codes described above. On the other hand, 'material type' refers to the composition of the FW, i.e. food, associated inedible parts, or both.

5.2.3 Categorisations of FW based on other criteria

Apart from the food sector to which the FW belongs to, FW can be categorised with regard to its nutrient composition (e.g. carbohydrate and fat content (Russ & Meyer-Pittroff 2004)), chemical composition (e.g. C, H, N, O, S and Cl content (Hla & Roberts 2015)) or storage temperature (e.g. ambient, chilled or frozen (Mena et al. 2011)). These are useful data to classify FW based on its characteristics. Nonetheless, the information provided with these examples is not enough detailed to facilitate the selection of the most suitable FWMS.

In the UK, WRAP also identified the stages of the FSC where FW was generated (e.g. at manufacturing or retail level), which is relevant since FW from some stages of the FSC cannot be managed in certain ways (e.g. catering waste should not be used for animal feeding (The European Parliament and the Council of the European Union 2009a)). WRAP also assessed the edibility of FW, classifying FW into avoidable (parts of the food that have been edible), unavoidable (inedible parts of the food, such as egg shells and bones) and possibly avoidable (food that some people would have eaten and others do not, such as bread crusts and potato skins) (Bridgwater & Quested 2013). Several authors have further classified FW at the household level as cooked/uncooked, as unpackaged/packaged FW (when waste is packaged, it is additionally sorted as opened/unopened packaging) and according to their reason to disposal (Ventour 2008, Quested & Murphy 2014, Bernstad Saraiva Schott & Andersson 2015). Leftovers and untouched food which goes to waste have also been identified by other researchers, for instance Matsuda et al. (2012). Considering these options is useful for a more detailed categorisation, but there is still a lack of categories that further classify FW in a way that some FWMSs can be prioritised against others based on sustainability performance, e.g. single ingredient or mixed product. Furthermore, some of these classifications have been applied to household FW only, and a comprehensive categorisation must include all stages of the FSC.

Lin et al. (2013) used a more detailed categorisation where FW falls into the following categories: organic crop residue (which includes fruits and vegetables), catering waste, animal by-products, packaging, mixed FW and domestic waste. In this study the potential for valorisation and some of the most appropriate options to manage FW were assessed for each FW type. However, the edibility of FW and whether the food was fully processed during manufacturing were not considered.

Edjabou et al. (2015) classified FW into two major categories: vegetable or animal-derived FW, and avoidable-processed, avoidable-unprocessed or unavoidable FW. A more explicit classification with sub-categories was also suggested by Lebersorger & Schneider (2011), who classified FW into three main types, based on its avoidability, life-cycle stage and packaging. The new category introduced, i.e. life-cycle stage, might be confusing because it does not refer to the stage of the FSC where FW was generated nor to the specific point of the product life cycle where food became FW, but rather to the edibility and final use of the FW. Therefore, life-cycle stage is rather a more detailed assessment of the avoidability of the FW. In this way, non-avoidable FW is named ‘preparation residues’, and avoidable FW can be classified into ‘leftovers’, ‘whole unused food’, ‘part consumed food’ and ‘not classifiable remainder’. This classification has been used to categorise household FW only.

From a different angle, the seven wastes from lean theory, also known by its Japanese translation as mudas, consist of transport, inventory, motion, waiting, overproduction, over-processing and defects. Chabada et al. (2013) used that seven-waste approach to classify categories of FW in fresh foods and determine the causes of waste generation, but not to identify solutions for FWM.

In summary, a comprehensive and exhaustive analysis of all types of FW to support sustainable FWM has yet to be published. A holistic approach, where all relevant sub-categories of FWs are identified and assessed, is necessary to identify sustainable FWMS. This FW categorisation should be used to propose or discard potential solutions for FWM. A solution to fill this knowledge gap is described in Chapter 7.

5.3 Methodologies and tools to support food waste management

An increasing number of articles have been published over the last years not only to identify sustainable solutions for FWM, but also to propose strategic decision-making approaches to support the identification of such solutions. These approaches consist in methodologies, frameworks, decision-support systems and software tools. This section reviews and analyses existing approaches to support sustainable management of FW.

Models to support decision making were first applied to waste management in the late 1960s (Karmperis et al. 2013). Whilst the first solid waste management models were optimisation models, later models were compromising models, which assume that the decision maker may have limited knowledge of the waste management problem, and are focused in integrated waste management and its sustainability implications (Morrissey & Browne 2004).

Chang et al. (2011) published a comprehensive review of simulation and optimisation models for solid waste management developed before 2010, dividing them into systems engineering models, systems analysis platforms and system assessment tools. They concluded that there is a lack of a whole waste-management cycle approach. Ness et al. (2007) categorised tools for sustainability assessment into three main categories: indicators/indices, product-related assessment and integrated assessment, and concluded that most sustainability tools actually focus on environmental ramifications only, disregarding economic and social implications.

The most widely used decision support frameworks are life-cycle assessment, cost–benefit analysis and multi-criteria decision making (Morrissey & Browne 2004, Karmperis et al. 2013). The following sub-sections review these frameworks, providing examples of their use and identifying software tools that support the use of the aforementioned frameworks.

5.3.1 Life-cycle assessment

Life-cycle assessment (LCA) is a methodology to assess environmental impacts associated with all life cycle stages of a product, i.e. raw materials extraction, manufacture, distribution, use, repair and end of life (generally, disposal or recycling). In this context, the term 'product' refers to both physical goods and services, and often the analyses refer to the function of the product rather than to the product itself (Guinée et al. 2004). LCA has been proven to be a useful method to identify opportunities for pollution prevention and for increasing efficiency of industrial practices (Rebitzer et al. 2004).

The LCA procedure has significantly developed during the last decades, and some specific areas with regard to databases, quality assurance, consistency and harmonization of methods have experienced notable improvements (Finnveden et al. 2009). Allesch & Brunner (2014) reviewed 151 articles that investigated decision support for waste management and concluded that 41% of the studies were based on LCA.

LCA uses life-cycle inventory data to facilitate the assessment of environmental indicators for different products. Some of the most significant impacts usually analysed with LCA are climate change, stratospheric ozone depletion, photooxidant formation (smog), eutrophication, acidification, toxicological stress on human health and ecosystems, resources depletion and noise. There are different modelling possibilities and methodologies that support calculation of these impact indicators from life-cycle inventory data (Pennington et al. 2004). However, converting the results of each impact indicator to a single score is intricate, since it requires the use of value judgments. This can be done in different ways, for instance by using previous knowledge and experience of the commissioner of the study or the LCA user, or preferably through the use of an expert panel, but in any case it cannot be done based solely on natural science (Scientific Applications International Corporation 2006).

Due to the widespread use of LCA in many areas of the world and its application to assess very different products, the usage of LCA has been standardised by the International Organization for Standardization. Currently, the following two standards apply:

1. ISO 14040:2006, which describes the principles and framework for LCA, including the definition of the four main phases of LCA: goal and scope, life-cycle inventory analysis (LCI), life-cycle impact assessment (LCIA) and life-cycle interpretation. ISO 14040:2006 also provides a reporting and critical review of LCA, and describes limitations of LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements (ISO 2006a).

2. ISO 14044:2006, which specifies requirements and provides guidelines for the phases and areas described in ISO 14040:2006 (ISO 2006b).

In order to compare LCA results for different products or production processes, it is important to use consistent data and not to mix information from different data sources or obtained from different methodologies. The three most widely used methodologies to undertake an LCA are CML, EDIP and Eco-indicator 99 (Laurent, Clavreul, et al. 2014). CML is a method developed by the Centre of Environmental Science of Leiden University which includes a set of impact categories and characterization methods for the impact assessment step (Pré Consultants 2016). EDIP includes the modelling of dispersion of substances and subsequent exposure increase, along with background exposure and vulnerability of target systems (Hauschild & Potting 2005). Eco-indicator 99 allows representing the environmental impact of a product with a single score. This is achieved in three steps: obtaining an inventory of emissions, resource extractions and land use across the life cycle of a product; calculation of damages to human health, ecosystem quality and resources; and weighting the damage categories (Ministry of Housing, Spatial Planning and the Environment (The Netherlands) 2000). Another noteworthy methodology is ReCiPe, which is based on both CML and Eco-indicator 99, and comprises harmonised category indicators at the midpoint level (such as acidification, climate change and ecotoxicity, from CML) and the endpoint level (such as damage to human health and damage to ecosystem quality, from Eco-indicator 99) (Goedkoop et al. 2013).

Life-cycle inventory data is usually obtained from databases. The most widely used databases to undertake an LCA for solid waste management systems are EcoInvent, BUWAL and EASEWASTE (Laurent, Clavreul, et al. 2014). Data collection and subsequent impact calculation are commonly laborious tasks. Because of this, the use of software to undertake an LCA has spread during the last decades. Currently, there are a number of commercial software packages specific for LCA. The most used software tools to undertake an LCA for solid waste management systems are SimaPro, EASEWASTE, GaBi and ORWARE. Some of these software packages, such as EASEWASTE, SimaPro and GaBi, have embedded their own life-cycle inventory data (Laurent, Clavreul, et al. 2014). Table 5-1 shows the most relevant software tools for LCA and remarkable examples of their use to model waste management in the last 10 years.

LCA is a useful tool to model waste management systems (Winkler & Bilitewski 2007). Although LCA usually considers the entire life cycle of a product, LCA for waste streams generally narrows the analysis to the life cycle of the waste material, from the point the

Table 5-1. Most relevant LCA software tools and examples of their use to model waste management

Software tool	Reference
SimaPro	Hung et al. (2007), Kaufman et al. (2010), Sevigné-Itoiz et al. (2015), Panepinto et al. (2015)
EASETECH/EASEWASTE	Christensen et al. (2007), Martinez-Sanchez et al. (2016), Cristóbal et al. (2016), Turner et al. (2016), Manfredi & Cristobal (2016)
GaBi	Tagliaferri et al. (2016), Ameli et al. (2016)
ORWARE	Eriksson et al. (2002), Eriksson et al. (2014)
IWM2	Winkler & Bilitewski (2007), Gentil et al. (2010)
DST	
WISARD	Gentil et al. (2010)
WRATE	
SSWMSS	
TRACI	Hodge et al. (2016), Soltani et al. (2016)
Total 3	Kim & Kim (2010)
ARES	Winkler & Bilitewski (2007)
EPIC/CSR	Winkler & Bilitewski (2007), Gentil et al. (2010)
SPIonexcel	Cherubini et al. (2009)

product is discarded until the waste has either been converted into a new resource (e.g. a recycled material or recovered energy), or when the waste has finally become part of the ecosphere (Hauschild & Barlaz 2009).

Although 50-60% of the publications between 2000 and 2015 that used LCA to assess solid waste management were dedicated to MSW management (Komilis & Ferrer 2017), there are several examples of LCA undertaken to study management of FW. Lee et al. (2007) analysed environmental ramifications of feed manufacturing, composting, incineration and landfilling of separate collection of FW and municipal solid waste (MSW) in Seoul and aggregated them into global warming, human toxicity, acidification, eutrophication and ecotoxicity. Khoo et al. (2010) evaluated environmental impacts of anaerobic digestion, composting and incineration of MSW in Singapore, although left some considerations out of the scope of LCA, such as transportation. Kim & Kim (2010) assessed dry and wet feeding, composting and landfilling of household FW but considered only global warming and resource recovery as environmental impacts. Liamsanguan & Gheewala (2008) used LCA to assess energy consumption and GHG emissions of incineration and energy recovery of MSW in Phuket, Thailand. Lundie & Peters (2005) compared the environmental performance of home composting, centralised composting and landfill of household FW and concluded that it is necessary to employ LCA in combination with other tools that address technical, social and microbiological risk implications to achieve an integrated assessment of the FW problem. Bernstad & La Cour Jansen (2012) compared 25 LCAs addressing FWMSs such as anaerobic digestion, composting, thermal treatment and landfill, and found significant differences between studies with regard to delimitation of system boundaries, methodological choices and variations in used input.

Most of the weaknesses identified for LCA methodologies and tools, such as those remarked by Karmperis et al. (2013) and Gentil et al. (2010), also occur when assessing environmental implications of different FWMSs with LCA. For instance, developing and using an LCA model is usually complex and time consuming; data available may be lacking; and LCA requires significant assumptions, such as boundary conditions, data sources, impact assessment criteria and weights, which are often subjective and even arbitrary. Furthermore, Laurent, Bakas, et al. (2014) asserted that LCA results from the study of MSW systems are strongly dependent on local conditions. Corrado et al. (2017) also noted that discrepancy in definitions of FW and the LCA approaches used significantly affect results from LCA. Consequently, a specific tool that considers the particularities of FW and FWM, and more specifically the unique conditions of a specific food manufacturing environment, would be advantageous to find targeted, bespoke solutions for sustainable FWM. This approach is also suggested by Notarnicola et al. (2017).

5.3.2 Cost–benefit analysis

Cost-benefit analysis (CBA) has been defined as a "systematic approach to estimating the strengths and weaknesses of technology alternatives that satisfy agency business requirements" (International Records Management Trust 2006). However, CBA is not only used to assess technology alternatives, but also to evaluate programmes, decisions, policy, or any project in general. CBA may be used for the following purposes (Mishan & Quah 2007):

1. Decide whether a project should be undertaken.
2. If there is more than one feasible project to undertake, decide which one to undertake.
3. At what level a manufacturing plant should operate.
4. What combination of outputs the company should produce.

For a project to qualify following a CBA, its social benefits (i.e. increases in human wellbeing) must exceed its social costs (i.e. reductions in human wellbeing) (Pearce et al. 2006). These benefits and costs must be converted into monetary values to be assessed by CBA, and include both real economic benefits/costs and non-marketed implications such as damages to health or the environment (namely externalities) (Finnveden et al. 2007).

A standard CBA is structured in seven steps: description of the context, definition of objectives, identification of the project, technical feasibility and environmental sustainability, financial analysis, economic analysis and risk assessment (European Commission 2014).

CBA has significant weaknesses. For instance, it is very complex, and inherently flawed, to translate all implications of a decision into monetary terms, e.g. consequences to human health and impacts to environment (Heinzerling & Ackerman 2002). The same authors claim that the case for CBA of environmental protection is, “at best, wildly optimistic and, at worst, demonstrably wrong”, and that CBA should not be used to assess environment implications of decisions. Arvanitoyannis (2008) also highlighted the problems of using CBA to support environmental policies due to its high uncertainty regarding the estimations of external environmental costs.

Despite its shortcomings, CBA has been previously used to analyse waste management systems. For instance Eshet et al. (2005) used CBA to analyse externalities of incineration and landfilling of waste, Jamasb & Nepal (2010) applied a social CBA to evaluate socio-economic implications of waste-to-energy systems and Aye & Widjaya (2006) applied both LCA and CBA to the assessment of anaerobic digestion, composting and landfilling. The Nordic Council of Ministers (2007) published an exhaustive guideline for CBA in waste management, and noted that CBA is only supposed to ‘assist’ in the decision making, since not all information can be captured in a CBA.

When applying a CBA in solid waste management, this methodology also presents significant weaknesses, such as those identified by Karmperis et al. (2013): valuing non-market goods is complex, comprehensive CBA models are time-consuming to develop, it is difficult to measure benefits and costs of a project with regard to its environmental impacts, and values of variables needed to model CBA may change and invalidate the simulation. Reich (2005) concluded that CBA is a very ambitious method, but it also lacks in transparency. Because of the reasons explained in this section, and also considering the lack of previous use of CBA to assess FWMSs, CBA is not considered a sound methodology to support sustainable management of FW.

5.3.3 Multi-criteria decision-making / multi-criteria decision analysis

Multi-criteria decision-making (MCDM) or multi-criteria decision analysis (MCDA) (hereinafter, both referred as MCDM) are methodologies to support decision making when there are multiple, usually conflicting, objectives in which the decision maker must choose amongst quantifiable or non-quantifiable and multiple criteria to reach a compromise solution

(Pohekar & Ramachandran 2004). MCDM usually consists of the following main steps (Opricovic & Tzeng 2004):

1. Establish criteria for system evaluation to relate system capabilities to goals
2. Develop alternative systems to achieve the goals
3. Evaluate options according to the criteria, applying a normative multi-criteria analysis method
4. Choose one option as optimal
5. In case the final solution is not accepted, collect more information and start the next stage of iteration

MCDM methods are advantageous because they are flexible methodologies, which take into account both qualitative and quantitative criteria, and allow considering and prioritising different stakeholders' views (Karmperis et al. 2013).

MCDM has been widely used to support waste management. There are a number of different MCDM methods, which generally differ in the type of decision criteria, type and number of alternatives, approach to compensation amongst decision criteria and preference ordering (Stefanović et al. 2016). The most relevant MCDM methods for waste management are briefly described and discussed in the next sub-sections.

5.3.3.1 Analytic Hierarchy Process / Analytic Network Process

The Analytic Hierarchy Process (AHP) is a MCDM methodology presented by Thomas L. Saaty in 1980. It comprises the following three major stages (Wind & Saaty 1980):

1. Decomposing the problem into a hierarchy of different levels
2. Establishing priorities amongst the elements in each level of the hierarchy by asking each stakeholder involved in the decision making to evaluate each set of elements on a pairwise basis
3. Calculating the priorities and consistency

The Analytic Network Process (ANP) is an extension of the AHP (Huang et al. 2011), and uses a similar procedure but adds a feedback loop for the different criteria and allows interrelations between them (Achillas et al. 2013).

There are a number of examples of the use of AHP to assess different waste management strategies, although AHP has been used mostly to decide location of waste treatment plants (Angelo et al. 2017). Vučijak et al. (2015) used AHP to evaluate criteria weights along with another MCDM method, namely VIKOR (explained in Section 5.3.4), to rank alternatives for MSW management based on environmental, economic, social and technical criteria. Su et al. (2010) assessed social, economic and management aspects of waste treatment practices combining LCA, TOPSIS (explained in Section 5.3.3.4) and AHP. Chen (2010) applied data envelopment analysis (a linear programming technique) and AHP to evaluate the efficiency of MSW generation, sorting and collection. Herva & Roca (2013) applied the ecological footprint and MCDM comprising AHP and two outranking methods (PROMETHEE and GAIA, described in Section 5.3.3.3) to assess the environmental performance of thermal plasma gasification, biological treatment of organic fraction with energy recovery from refuse derived fuel, incineration with energy recovery and landfilling of MSW.

A number of software tools can be utilised to support the use of AHP, for instance Herva & Roca (2013) used Microsoft Excel and MATLAB to establish criteria weights. Other examples of software tools are EXPERT CHOICE, HIPRE 3+ and LOGICAL DECISIONS (Morrissey & Browne 2004).

Nevertheless, AHP has rarely been used to assess FWM. Two isolated examples are the work by Chen et al. (2014), who used AHP to assess the safety of directing FW to animal feeding, and Babalola et al. (2015), who applied AHP to assess sustainability of animal feeding, rendering, anaerobic digestion, composting, incineration with energy recovery and landfilling to deal with food and biodegradable waste.

Hung et al. (2007) pointed out that AHP presents significant weaknesses to deal with real-world waste management decisions in which there are numerous stakeholders with different points of view, and proposed to combine AHP with a consensus analysis model (CAM). CAM allows assessing the degree of consensus between stakeholders, complementing AHP. This approach was applied by Hung et al. (2006) and Hung et al. (2007) to assess environmental, economic, social and technological considerations of hog feeding, anaerobic digestion, composting, incineration and landfilling of FW in Taiwan.

5.3.3.2 Multi-Attribute Utility Theory

The Multi-Attribute Utility Theory (MAUT) aims at expressing the preferences (namely utilities) of multi-attribute outcomes as a function of the utilities of each attribute alone (Torrance et al. 1982). MAUT has a similar procedure than that of AHP, and in fact AHP is sometimes classified as a MAUT approach (Dyer et al. 1992). MAUT comprises the following steps (Min 1994):

1. Identify the goals of the decision and define the problem scope
2. Define a set of attributes which affect the decision outcome and structure them in the form of a hierarchy
3. Obtain information of the attributes from the decision maker(s) and decide their relative importance
4. Establish functional relationships between the attributes and the utility scores, using probability distributions if relationships are uncertain
5. Calculate the overall utility score for each decision alternative and subsequently rank alternatives
6. Undertake a sensitivity analysis

MAUT has been applied to solve waste management problems. For instance, Kijak & Moy (2004) proposed a framework for MSW management that includes streamlined LCA, consideration of economic and social implications, data integration, valuation and interpretation. For valuation and interpretation, MAUT was used to assist with the integration of qualitative and quantitative information. The application of MAUT was aided by the use of the software package Criterium DecisionPlus 3.0, developed by InfoHarvest Inc. Binder et al. (2008) used MAUT to assess environmental, social and economic aspects of the use of radio frequency identification devices for waste and resource management.

One isolated example of the use of MAUT to assess different options for FWM is the work by Chadderton et al. (2016). They used a modified swing-weighting technique (namely SMARTER: Simple Multi-Attribute Rating Technique Exploiting Ranks) that allows the decision maker to identify the objective that is the most important to them and weigh the other objective relative to that one. MAUT was used to determine the overall utility of each alternative.

5.3.3.3 Outranking

Outranking procedures requires comparison between alternatives to be made in a pairwise fashion, which are characterised by the limited degree to which a disadvantage on a particular viewpoint may be compensated by advantages on other viewpoints (Pirlot 1997). For this reason, outranking methods have been classified as 'non-compensatory' or 'partially compensatory' methodologies (Pirlot 1997, de Boer et al. 1998). Outranking models deal well with both qualitative and quantitative attributes and with imprecise situations (de Boer et al. 1998).

ELimination and Choice Expressing REality (ELECTRE) and Preference Ranking Organization METhod for Enrichment Evaluations (PROMETHEE) are the most significant outranking models which have been used to evaluate different environmental issues (Huang et al. 2011, Karmperis et al. 2013), although no examples were found in which they were applied to assess FWMSs. ELECTRE was the most commonly used method to undertake waste management decisions up to 2004 (Morrissey & Browne 2004), but a more recent review by Huang et al. (2011) shows a decline in its use compared to other methods. ELECTRE needs weights of criteria, preference and indifference thresholds and veto thresholds; the latter two are determined by analysts (Hokkanen & Salminen 1997). Two relevant examples are the application of ELECTRE to assess management of MSW in Greater Athens area (Karagiannidis & Moussiopoulos 1997) and to assess management of solid waste in Uusima region in Finland (Hokkanen et al. 1995).

PROMETHEE includes the following steps: determination of deviations based on comparisons on a pairwise basis, application of the preference function, calculation of an overall preference index, calculation of outranking flows and calculation of the net outranking flow (Behzadian et al. 2010). Herva & Roca (2013) combined AHP with PROMETHEE and its complement Geometrical Analysis for Interactive Aid (GAIA), to assess the environmental performance of four different treatment options for MSW. They used the software Decision Lab 2000 (Visual Decision Inc., 2009) to apply the PROMETHEE/GAIA model. Bertanza et al. (2016) used the web application D-Sight to apply the PROMETHEE/GAIA model to evaluate the selection of a sewage sludge management strategy.

5.3.3.4 Technique for Order of Preference by Similarity to Ideal Solution

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) consists of finding the optimal solution by ranking alternatives based on the shortest distance from the positive ideal solution and the farthest from the negative ideal solution (Shih et al. 2007). TOPSIS has significant advantages compared with other MCDM methodologies, such as a sound logic that represents the rationale of human choice, a scalar value that accounts for both the most and least appropriate alternatives simultaneously, and a simple computation process (Kim et al. 1997). Shih et al. (2007) also considers as an important advantage that TOPSIS allows to visualise the performance measures of all alternatives on a polyhedron.

There are several examples of the use of TOPSIS to assess waste management scenarios. For instance, Su et al. (2010) used TOPSIS to integrate quantitative and qualitative analyses on the social, economic, and management aspects of waste treatment policies. Aghajani Mir et al. (2016) combined extended versions of TOPSIS and VIKOR (described in Section 5.3.4) to identify the optimal MSW management option. With regard to the application of TOPSIS to assess food systems, Roghanian et al. (2014) used TOPSIS to rank different suppliers in a FSC.

5.3.3.5 Conclusions of MCDM methods used to assess sustainability of waste management

The most used MCDM methods to assess environmental issues of waste management are AHP/ANP, followed by MAUT and PROMETHEE (Huang et al. 2011, Vučijak et al. 2015). In spite of their widespread use, MCDM models have a significant weakness: the evaluation criteria by decision makers and, specifically, the weight assigned in each criterion may be subjective (Karmperis et al. 2013). Huang et al. (2011) asserted that the different MCDM methods are ultimately similar and decision makers choose a method mostly based on familiarity and available opportunities, and finally recommends an integration of various methods and tools.

The challenge of identifying the most sustainable FWMS is a multi-criteria problem, since different and sometimes conflicting goals exist, which can be classified into environmental, economic and social goals. On many occasions, MCDM methodologies are used to make a decision when there are different stakeholders and/or decision makers. Nevertheless, as defined in the scope of research in Chapter 2, the research presented in this thesis aims to consider the food manufacturer as the sole decision maker, although there can be other stakeholders affected by that decision, and some of these are considered in the research scope, e.g. the wellbeing of citizens of the area is considered when defining social implications of FWM. Furthermore, in order to effectively use MCDM methods, a sound understanding of sustainability implications of FWM is needed. Chapters 7-9 present a novel methodological framework that support the evaluation of the aforementioned sustainability implications, which can be subsequently used by decision makers by using any of the MCDM approaches described in this section.

5.3.4 Other methodologies

There are a number of other methodologies to support decision making which can be used to find sustainable solutions for waste management, such as game theory and ASPID.

Game theory is “the study of mathematical models of conflict and cooperation between intelligent rational decision-makers” (Myerson 1991). It has been used in a wide range of applications, including waste management. Karmperis et al. (2013) analysed game-theoretic approaches in decision support models for solid waste management, focusing on the cooperative part of game theory. They presented the “waste management bargaining game framework”, which addresses the problem where the stakeholders negotiate over a surplus yielded through solid waste management systems, and the stakeholders are partially cooperative (they aim to reach an agreement) and partially conflicting (they have different objectives). Soltani et al. (2016) designed a framework for the selection of MSW treatment options, which models conflicting priorities of stakeholders over sustainability criteria. Game theory is subsequently applied to support stakeholders to decide how to share the costs and benefits fairly, guiding them towards an agreement on a sustainable solution.

The Analysis and Synthesis of Parameters under Information Deficiency methodology (ASPID) is a mathematical method based on the synthesis of fuzzy sets to determine weighting factors given in a form of equality or inequality, and can use non-numerical, inexact and incomplete information to generate results (Pilavachi et al. 2009, Stefanović et al. 2016). ASPID has been used to model energy systems, but it had never been used to assess sustainability of waste management practices until 2016 (Stefanović et al. 2016). Stefanović et al. (2016) used ASPID to assess environmental, economic and social performance of recycling, anaerobic digestion, composting, thermal treatment and disposal of waste, obtaining similar results as with AHP method.

Other methods that have been applied more rarely to waste management, or are bespoke solutions, are explained in this paragraph. VIKOR, which stands for Multicriteria Optimization and Compromise Solution in Serbian, was used by Vučijak et al. (2015) to rank alternatives for selecting the MSW management scenarios considering environmental, economic, social and technical aspects. Wang et al. (2012) used an interval-valued fuzzy-stochastic programming (IVFSP) approach to assess MSW management under uncertainty. IVFSP has the feature of being capable of reflecting the confidence of decision makers over subjective judgments. Harrison et al. (2001) presented a software-based decision-support framework for solid waste management that incorporates Microsoft Excel, Visual Basic for Applications (hosted by Excel), and the CPLEX LP solver. Khan et al. (2015) developed a decision model to assess techno-economic aspects of different MSW scenarios called FUNdamental ENgineering PrinciplEs-based ModeL for Estimation of Cost of Energy and Fuels from MSW (FUNNEL-Cost-MSW). Hanandeh & El-Zein (2010) presented the Stochastic Integrated Waste Management Simulator model, which provides a view of the environmental impacts and economic costs of MSW management options under conditions of uncertainty. Tan et al. (2014) presented a model supported by the software General Algebraic Modelling System which aims to predict the best mix of waste treatment technologies, forecast the production of by-product from waste treatment processes, estimate the facility capacity, forecast the GHG emissions of the system, and generate an optimal, cost-effective solution for MSW. Zaman & Lehmann (2013) proposed a 'zero waste index' for forecasting the amount of virgin materials, energy, water and greenhouse GHG substituted by the resources that are recovered from waste streams. Levis et al. (2013) presented the Solid Waste Optimization Life-cycle Framework to minimise costs and environmental impacts of the collection and treatment of solid waste. Rigamonti et al. (2016) defined a composite indicator to assess environmental and economic sustainability of integrated MSW management systems. Similarly, Wilson et al. (2015) presented a qualitative-quantitative indicator set for integrated waste management to allow benchmarking of a city's performance in terms of its sustainability performance. Xu et al. (2016) used a stakeholder analysis and social network model to analyse management of household FW. Bergeron (2017) presented an Analytical Method of the Waste Allocation Process to describe, classify, explain and predict outcomes of waste management systems. Ho et al. (2017) presented a novel method known as Waste Management Pinch Analysis to identify waste management strategies based on specific targets. With regard to FWM, Manfredi & Cristobal (2016) proposed a methodology based on LCA (supported by EASETECH), multi-objective optimisation and Pareto optimality concepts to quantitatively evaluate the environmental and economic performance of FWM options.

5.3.5 Applicability of existing methodologies to support food waste management

Allesch & Brunner (2014) reviewed 151 articles that investigated decision support for waste management and concluded that below 20% of the studies analysed impacts on the three pillars of sustainability: environmental, economic and social implications. Typically, methodologies consider one of the pillars only, e.g. LCA assess environmental impacts, whilst its counterpart Life-Cycle Costing (LCC) analyses economic performance and Social Life-Cycle Assessment (SLCA) assesses social implications (Klöpffer 2003). More recently, it has been proposed to integrate these methodologies into a Life-Cycle Sustainability Analysis (LCSA), which can be used to assess all sustainability implications of an activity or product in its life cycle (Kloepffer 2008). In 2006, the European Commission started the Coordination Action for innovation in Life-Cycle Analysis for Sustainability (CALCAS) project, which generated a framework for LCSA (Guinee et al. 2010). This is a young research area that still needs to be further developed and tested in a variety of situations. Literature on LCSA of FWM or, more generally, waste management, is lacking. Furthermore, LCSA presents similar problems than those of LCA, as discussed in Section 5.3.1: complexity, availability of data, subjectivity of the criteria chosen and difficulty to extrapolate local results to obtain general conclusions.

Generally, methodologies and tools focus on different aspects of reality. Therefore, a combination of them can provide a more holistic description of the real situation and offer additional advantages (Ekvall et al. 2007, Achillas et al. 2013). For instance, Angelo et al. (2017) successfully combined LCA and MCDM (supported by the software tool VIP-analysis) to assess management of household FW from Rio de Janeiro. Arena & Di Gregorio (2014) and Martinez-Sanchez et al. (2015) used a LCC approach to assess economic, social and environmental costs. Nevertheless, this brings the challenge of collecting and managing large amounts of information, due to the assessment needed to analyse different aspects of waste management, e.g. environmental, economic and social ramifications.

Furthermore, developing frameworks and tools which are case and site specific, for instance for FWM and for one particular food company, may provide additional benefits (Ness et al. 2007, Pires et al. 2011). Up until now, there are not enough examples of methodologies for waste management applied to FWM, and bespoke methodologies for FWM are lacking.

Hence, there is a clear need to harmonise the different methods to assess the sustainability implications of waste management and apply them to FWM. The research area of FWM would benefit from a holistic approach to identify the most relevant attributes for FWM and develop a framework for its management. This would facilitate the collection and use of large amounts of data. As a result, bespoke solutions to manage FW more sustainably can be proposed. Holistic approaches were also suggested by Lee et al. (2016) to assess management of MSW.

Del Borghi et al. (2009) proposed a useful approach to waste management which includes: definition and categorisation of waste streams, development of a waste hierarchy to guide preferential order of different options and identification of specific, key environmental indicators. This seems to be a helpful initial approach that can be applied to FWM and it is explored in Chapters 7 and 8.

5.4 Chapter summary

This chapter has reviewed the most relevant categorisations of FW and methodologies and tools that can be used to support FWM. It was concluded that there is a lack of a comprehensive and exhaustive analysis of all types of FW with the final aim of supporting sustainable FWM. Furthermore, a sound FW classification is the first step needed to identify the most sustainable solution for FWM. A novel FW categorisation, developed with this aim, is presented in Chapter 7.

A number of methodologies and associated software tools that have been used to assess waste management systems have been reviewed. They have been classified into LCA, CBA and MCDM methods. Some of the methodologies have not yet been applied to FWM problems. Strengths and weaknesses of each methodology have been identified, and their applicability to FWM systems has been discussed. Consequently, the need for specific, bespoke methodologies for FWM has been identified. A starting point would be to assess sustainability implications of FWM. Chapters 7-9 present a novel systematic framework to assess the aforementioned sustainability implications. This can be subsequently used by environmental managers to assess environmental impacts with LCA, financial managers to analyse economic performance and finally decision makers by using any of the MCDM approaches described.

CHAPTER 6 RESEARCH METHODOLOGY

6.1 Introduction

This chapter explains the research methodology used in this thesis. It starts by providing a definition of 'research' and an overview of different research types and methodologies, discussing the applicability of each. At the end of the chapter, the research methodology selected in this thesis is presented and justified.

6.2 Overview of research types

Research constitutes "creative and systematic work undertaken in order to increase the stock of knowledge – including knowledge of humankind, culture and society – and to devise new applications of available knowledge" (OECD, 2015). According to this source, every research activity must be novel, creative, uncertain, systematic, and transferable or reproducible.

Research activities are very diverse and can be divided into several research types. Kothari (2004) described different types of research according to a set of criteria, which can be seen in Figure 6-1 and are described below. In each section of the diagram, one research type, or a mixture of both is used. This means that each piece of research belongs to one research type for each research criteria (according to Figure 6-1).

Descriptive research aims to describe and report situations that exist at present through measures and without any control over the variables. On the other hand, analytical research uses information already available to make a critical analysis of the situations and draw conclusions.

Figure 6-1. Stages to decide different types of research. Based on Kothari (2004)

Applied research looks at the applicability of the research to modify some phenomena and gain a benefit from it, solving a specific problem. On the other hand, fundamental (or basic) research is aimed at gaining an understanding of observed phenomena and predicting how they will behave in the future, adding information to the existing body of knowledge.

Quantitative research seeks to confirm or refute a pre-established hypothesis through objective measurements, for instance by using experiments and collecting data, in which numerical results are obtained. Qualitative research is concerned with qualitative phenomena, such as opinions and behaviours, and it may use interviews, surveys, tests and tools alike to obtain results. Quantitative research is more commonly used in physics, engineering and similar disciplines, whilst qualitative research is typically more useful in social and business research.

Conceptual research is related to abstract ideas and theories, and it is used to develop new ideas or to reinterpret existing ones. Empirical research uses empirical evidence, i.e. generating knowledge through experience and observation. Empirical research uses experiments to generate results, generally manipulating some variables and analysing the effects caused in others, whilst conceptual research seeks the development of new or existing theories generally without experimentation.

Research activities can be classified in further groups. Kothari (2004) also identified and described additional types of research, including *one-time research* or *longitudinal research*, depending upon the number of time periods used to carry out the research; *field-setting research*, *laboratory research* or *simulation research*, depending upon the environment in which the research is developed; *exploratory research* or *formalized research*, depending on whether the research attempts to develop or test theories; and *conclusion-oriented research* or *decision-oriented research*, depending upon the freedom the researcher has to decide the scope of the research.

In spite of the classification described above, numerous research activities are currently carried out using a combination of different research types. This type of 'multi-method research' has the advantage of benefitting from the strengths of each research method utilised, which is particularly useful in research that involves several phases. A multi-method research enables the use of a more holistic approach to address the research area under investigation.

In addition to the research types described above, Technology Readiness Level (TRL) is a useful tool to categorise research activities. TRL was developed by the National Aeronautics and Space Administration (NASA) during the 1970-80s in order to assess maturity of particular technologies and enable a consistent comparison of maturity between them (EARTO, 2014). TRLs are based on a scale from 1 (early/blue sky research) to 9 (the most mature technology), as shown in Figure 6-2. TRLs are widely used by organisations, industries and businesses to enable planning of future development stages and timescales for a particular technology.

6.3 Research methodology

This section explains the research methodology applied in this thesis, based on the types of research identified in the previous section. It also describes the various phases in the development of the research.

6.3.1 Type of research used in this thesis

The different research types described in the previous section have been considered when devising the research methodology to be used in this work. Following the stages listed in Figure 6-1, the research types that best describe the methodology used in this research are:

- Analytical research: the present research aims not only to understand the existing FWM practices, but also to critically analyse FWM issues to propose alternative solutions or approaches in which FWM is improved with regard to sustainability criteria. The alternatives proposed are also discussed and analysed in the context of required improvements.

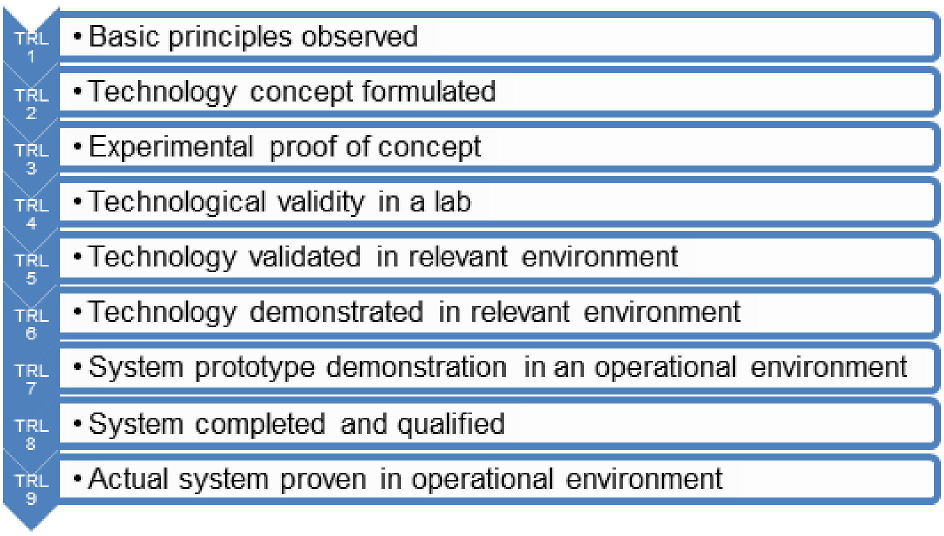


Figure 6-2. Technology Readiness Levels. Based on EARTO (2014)

- Fundamental research: the present research attempts to improve FWM through an analysis of current situations and proposed alternatives, but does not specifically consider the development of new technologies. The solutions described are proposed for the food industry, but it is their ultimate decision whether to apply them or not; however, the results predicted from their implementation have been estimated. Furthermore, the present research is computer based (based on framework development, modelling and simulation) rather than based on laboratory investigations.

- Qualitative and quantitative research: the present research incorporates aspects of both qualitative and quantitative research, as it studies qualitative issues (e.g. edibility of food, reasons for FW generation, feasibility of redistribution) and quantitative matters (e.g. amount of food being wasted, economic costs, emissions of greenhouse gases). When generating and analysing results, both qualitative and quantitative outcomes are examined in the context of sustainability in FWM.

- Conceptual research: the present research aims to develop new approaches to FWM through the development of a novel framework, FW categorisation and terminology. This research is not built upon direct observations or laboratory experiments made by the author of the thesis, but it is based on the analysis of previous experiences and research carried out by other researchers and industries.

In addition to the main four stages to define different types of research (Figure 6-1), the present research also incorporates aspects of simulation research and field-setting research. Initially, the present research focuses on modelling and simulating FWM practices currently used in the food industry and also feasible alternatives. However, the use of case studies to prove the research validity is related to field-setting research, as it includes industrial visits, data collection, and consultation with company employees from various food industries.

It is important to note that a range of research approaches have been utilised within each research category. For instance, the analytical research has been chosen over descriptive research, nonetheless the literature review chapters of the thesis include a descriptive study of FWM issues and practices. In conclusion, the research types described above are the ‘predominant’ research types used, and a ‘multi-method’ research approach was used in most of the work presented.

Regarding the maturity of the research work, the Technology Readiness Level of this research is 2-4. The basic principles have been observed through an exhaustive review of FWM practices and a study of state-of-art alternatives. Novel approaches to the issues identified have been formulated and tested via case studies in the food industry. Although the validity of the research ideas proposed have been demonstrated via industrial case studies and discussed, a universal applicability would have to be proven through further research.

Not only do different disciplines (e.g. engineering and social sciences) necessitate different research types, but also the different economic sectors require bespoke research methodologies. The research described in this thesis falls into the scope of industrial engineering, which encompasses very varied sectors, such as automotive, aeronautical, chemical and pharmaceutical. The sector under consideration must be assessed in detail to understand its distinctive characteristics. In the case of the food sector, there are a number of unique aspects to consider. For instance, legislation is very strict in order to protect consumers, with high attention paid to issues such as food safety and traceability. Perishability is also of high relevance, as numerous types of food have a short shelf life compared to other products. FW can also be considered perishable, as its natural degradation tends to occur very rapidly; this highlights the fact that time is one of the most important variables to consider when managing FW. In addition, compared to other products, foods (and FWs) are very heterogeneous materials. The research solutions proposed in this thesis take into account these and other particularities of FWM. For instance, the qualitative parameters presented in Section 7.4 and quantitative parameters presented in Chapter 8 were proposed taking into consideration the aforementioned particularities of FW and the food industry, and are bespoke to the food industry and FWM environments.

In recent years, the growing issue of FW has attracted the attention of international research. Numerous research projects are currently looking into consumer behaviour towards FW generation, commonly using descriptive, qualitative research. Alternatively, a more well-developed area of research uses applied, quantitative, empirical research to assess different alternatives to manage FW and their outcomes, e.g. anaerobic digestion or composting. The author of this thesis is aware of those research efforts and took an innovative mixed approach: using existing applied, quantitative, empirical research to assess FWMSs in order to propose solutions to manage FW more efficiently through conceptual research.

6.3.2 Phases of the research methodology

The research described in this thesis has been developed taking into consideration the viewpoints mentioned in the previous section. Following those factors, the research was developed in four different phases: research definition and literature review, framework development and implementation, testing and validation, and research evaluation. These phases are outlined in Figure 6-3 and described below:

a) Research definition and literature review

Using the author's prior knowledge and experience in the food industry, the first stage involved the identification of the research problem and definition of research to be done. Secondly, in order to understand better the FW issue, relevant literature was reviewed around three areas: ramifications and issues associated with the generation and management of FW, options to tackle the FW issue, and categorisations and tools for FWM. The descriptive, qualitative-quantitative research carried out around these four areas enabled the identification of major challenges in management of FW, directing towards an analytical research approach. As a consequence of this analysis, the research assertions, hypotheses and objectives (i.e. research scope) were precisely defined.

b) Framework development

The conclusions drawn in the previous phase were utilised to propose new approaches to FWM. Specifically, a framework based on five stages has been developed to support decision making in FWM: delimitation of the boundaries of the food system, identification of FW types, qualitative and quantitative categorisation and quantification of FW types, identification of feasible FWMSs and sustainability analysis. The last stage, i.e. sustainability analysis, comprises the definition of quantitative attributes and the identification of connections and dependencies amongst attributes, design of a network of information flows for FWM, and a proposed scheme to identify optimal calculation steps of attributes.

c) Testing and validation

The proposed framework has been applied in a series of case studies at two relevant food industries to test its validity and practicality. Data were collected from two food companies and used to generate proposed solutions and these results were fed back to the two companies to enable them to manage their FW in a more sustainable way. In order to obtain results, both qualitative and quantitative indicators were used. The results generated were analysed and utilised to refine the proposed framework.

d) Research evaluation

The final research results and findings were analysed and discussed in order to draw research conclusions. Areas for further research which could be built on this work were identified.

6.4 Chapter summary

This chapter gives an overview of different research types and methodologies, highlighting their applicability to different research areas. A justification of the research methodology chosen to meet the objectives established in Chapter 2 is subsequently presented. The four main phases used to develop the research are briefly described. The first phase (namely Research definition and literature review) comprises the definition of research context and scope, which is described in Chapter 2. The first phase also includes a review of literature on FWM, which is presented in Chapters 3-5. The remainder of thesis addresses the phases 2-4: the second phase (Framework development) is described in Chapters 7-9, the third phase (Testing and validation) is addressed in Chapter 10, and the fourth phase (Research evaluation) is presented in Chapters 11 and 12.

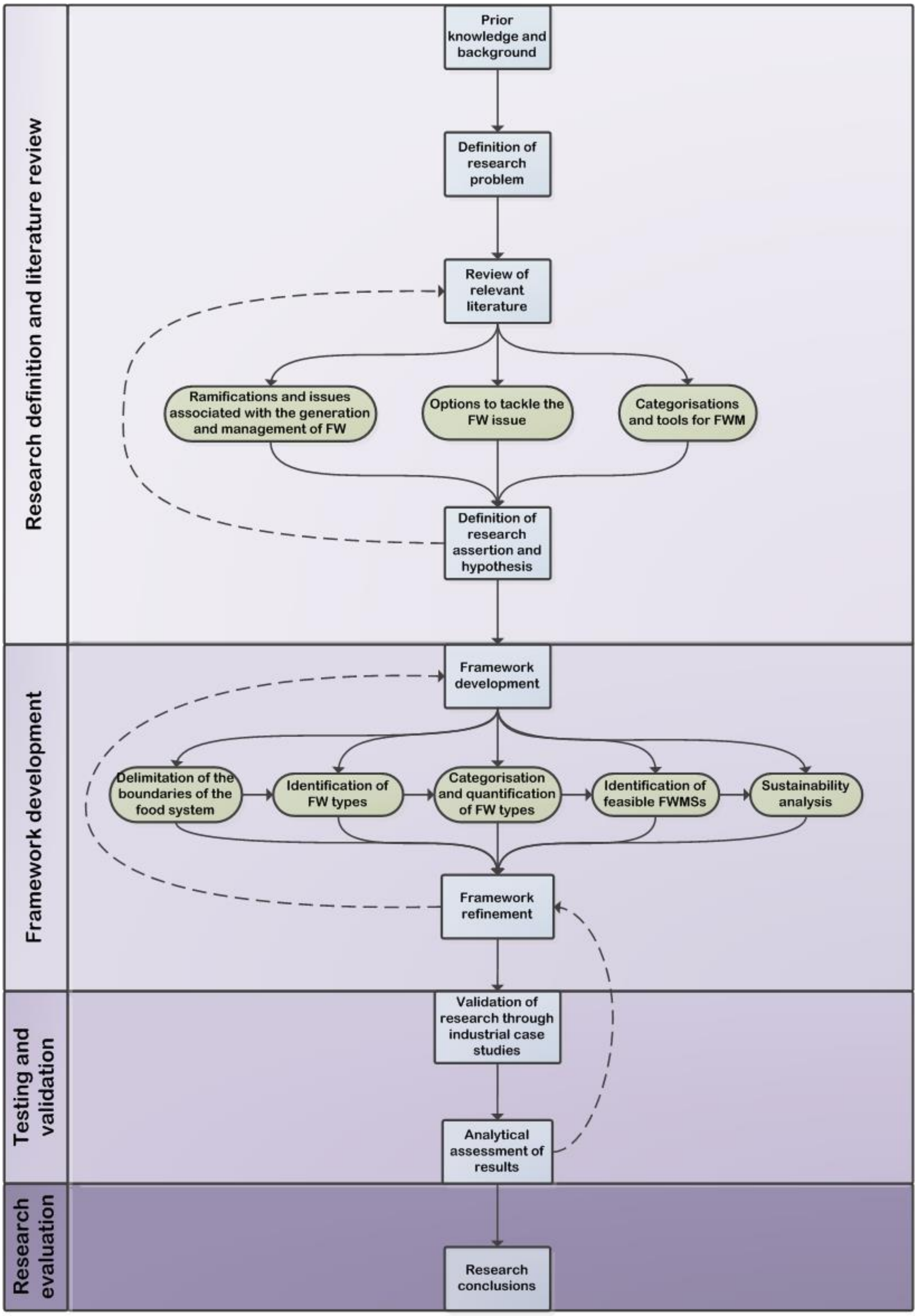


Figure 6-3. Research methodology

CHAPTER 7 A FRAMEWORK FOR IDENTIFICATION OF FOOD WASTE TYPES AND THEIR MOST SUSTAINABLE WASTE MANAGEMENT SOLUTION

7.1 Introduction

This chapter presents a framework to analyse FW to support the identification of the most sustainable FWMS. The first stage of the FWM framework is also described in this chapter, which is complemented by the research described in Chapters 8 and 9. Firstly, a consistent definition of FW and the food system is provided, which is used throughout the rest of the thesis. Secondly, a terminology and methodology to support the identification of FW types in a business is presented. Thirdly, qualitative parameters to assess characteristics of FW identified in the previous stage are described. Finally, these parameters are used along with the FWH to build a methodological procedure that enables the identification of the most sustainable solution for FWM.

Food companies (and any business) make decisions based primarily on economic considerations in order to maximise profit. In the case of FWM, the availability of waste management facilities can be a predominant factor to decide which FWMS to use. Furthermore, legislation limits the range of solutions applicable to manage different types of FW and therefore the decision is often made considering only a few alternatives.

In recent years, more research has been looking at additional implications of FWM including environmental and social results. More attention has been directed towards environmental impacts of FW, and currently there are tools and data available to measure greenhouse gas emissions, emission of pollutants to wastewater, and other environmental impacts from FWM facilities. However, as discussed in Chapter 5, most of the research examines only one type of impact (economic, environmental or social impact), and only very recent research aims to expand the scope and consider two or even all three types of aforementioned implications.

The research presented in this thesis aims to consider the three pillars of sustainability (economic, environmental and social ramifications) in the decision-making process so that more sustainable solutions can be achieved from the range of feasible waste management options. A visual model of the research approach used can be seen in Figure 7-1, which consists of providing a clear definition of the food system and the FW concept, identification of FW types in the food company under consideration, categorisation and quantification of FW identified, identification of suitable FWMSs, assessment of sustainability implications of each suitable FWMS, and selection of the most sustainable FWMS. Del Borghi et al. (2009) proposed a similar approach to waste management (not specific to FWM) which includes: definition and categorisation of waste streams, development of a waste hierarchy to guide preferential order of different options and identification of specific, key environmental indicators.

The framework presented in this chapter can be used to analyse all types of FW, including inedible by-products associated with food products. It can also be applied to any stage of the FSC, from farm to fork, although it is more useful and beneficial to analyse FW generated in the beginning of the FSC (e.g. during agricultural and manufacturing activities) since these FWs are generally more homogeneous than FWs from the end of the FSC. On the other hand, household FW is formed of a mix of food and non-food materials that complicates its management. The applicability of the framework is also discussed in more detail in Section 7.5 and tested in Chapter 10.

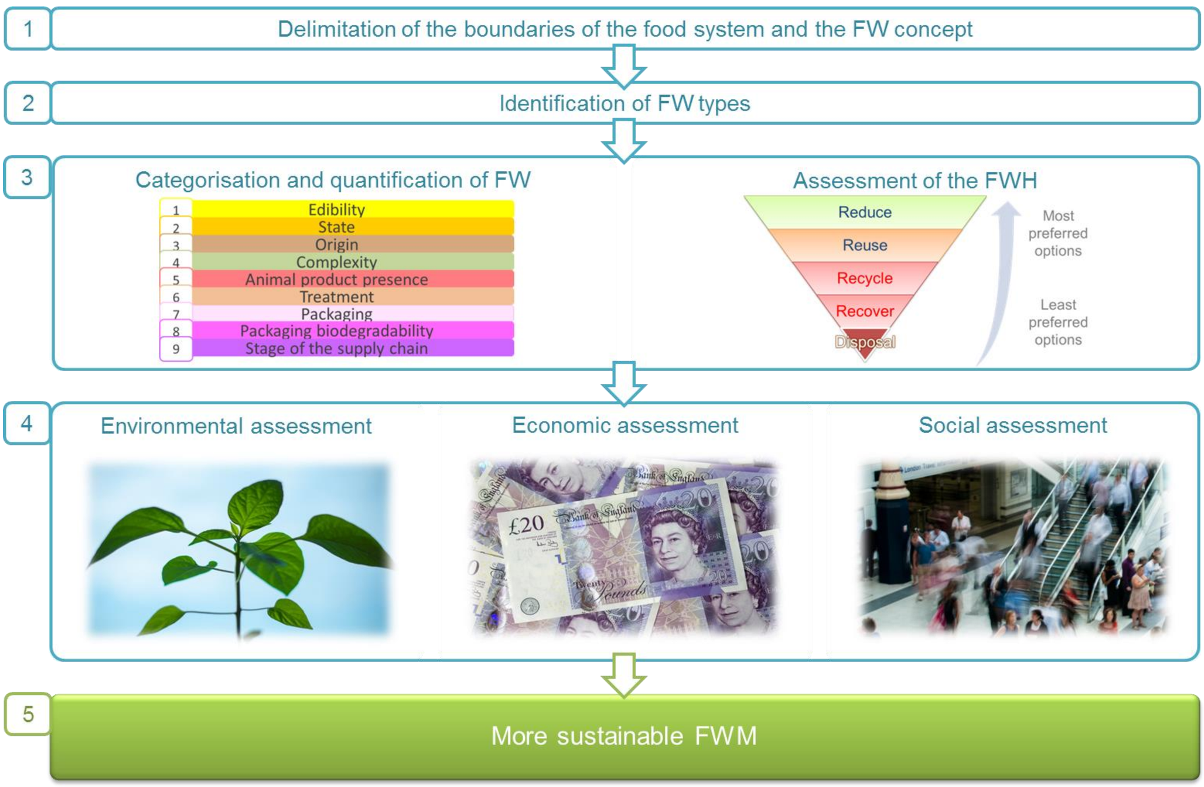


Figure 7-1. Structure of the research approach proposed

7.2 Definitions of food waste and the food system

In order to systematically assess FW generated in a company or stage of the FSC and improve its management, the first aspect to consider is to unambiguously define the exact meaning of 'food waste', as well as delimit the boundaries of the food system under analysis. A comprehensive analysis of the terminology used by different organisations is presented in this section. As a result, novel definitions of FW and food systems are proposed and discussed.

7.2.1 Definition of food waste

Despite the concept of 'food waste' initially seeming to be easy and commonly understood, there is not a global consensus on the exact meaning of this concept. In this section different definitions of 'food waste' by the most relevant organisations are reviewed and their applicability and appropriateness are discussed, with the final objective of conceiving the most pertinent definition to be used throughout this thesis.

Waste has been defined as "any substance or object which the holder discards or intends to discard" (The European Parliament and the Council of the European Union 2008). However, when adapting this definition to FSCs, FAO differentiates between food loss (generated generally in the beginning of the FSC: at production and manufacturing stages) and food waste (occurring at the end of the FSC, when the food has been fully processed and packaged). Both concepts are included in the more general term 'food wastage' (FAO 2011) (Figure 7-2). The same terminology is used by Lipinski et al. (2013), from the World Resources Institute.

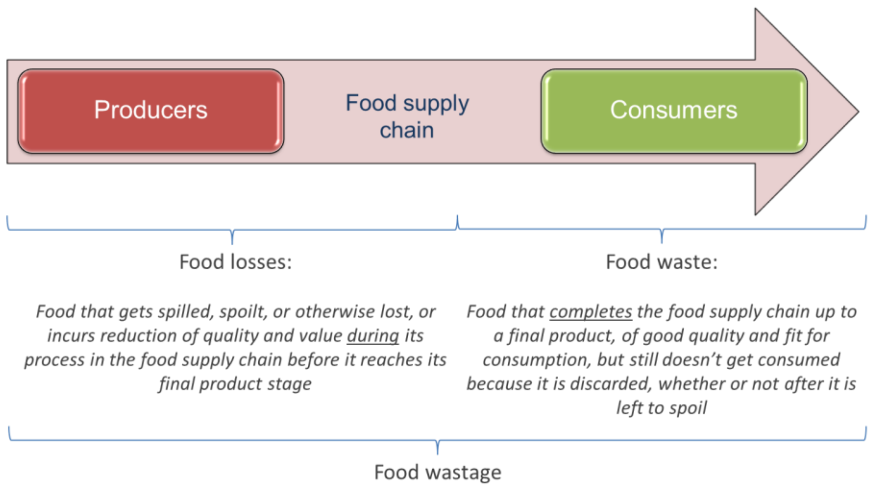


Figure 7-2. Definitions of 'food wastage', 'food losses' and 'food waste', according to FAO (2011) and Lipinski et al. (2013). Definitions from (Think.Eat.Save 2014)

These definitions create some concerns, since the concepts ‘food loss’ and ‘food waste’ would cover different stages of the FSC for different companies, geographical areas and food products. For instance, if sandwiches are produced in a factory and then sent to a retailer, the leftovers would be named ‘food waste’ at the retailer and ‘food loss’ at the factory; however if the sandwiches are produced directly in the point of sale in a retail company, the refuse would be named ‘food loss’, even when it has been generated at the retail level. In this case, although the stages of the FSC are the same (i.e. retail stage) the definitions would be different in each specific situation. The problem is aggravated when comparing different countries, since their FSCs are different and therefore systematic comparisons amongst them would be largely difficult. Contrary to the above, FUSIONS (2014) and Quested & Johnson (WRAP) (2009) name all these concepts as ‘food waste’, since both types of food wastage are similar in composition. This approach simplifies the assessment of this issue, as there would be no need to distinguish between two very similar concepts.

There is also disagreement about considering inedible parts of food (e.g. fruit stones and meat bones) as FW: FAO (2011) and Lipinski et al. (2013) only include parts of the food that could have been eaten by people in their definition of FW. By contrast Quested & Johnson (WRAP) (2009), the European Commission (DG ENV) (2010) and FUSIONS (2014) also consider inedible materials as FW. It is generally unmanageable to separate edible and inedible parts of the food for their quantification and treatment. For instance, a wasted banana would normally consist of the inedible skin and the edible flesh, and it would not be peeled before it is treated or disposed of. Additionally, inedible FW is generated in very high quantities and an optimisation of its management is also needed, therefore a definition of ‘food waste’ including inedible parts of the food is more advantageous.

Another major discrepancy involves the planned use of food: the intended use of it in a different way than for human consumption (such as growing crops for feed or bioenergy generation) is not considered FW by any of the aforementioned organisations; whilst the unplanned use of it in a non-food use is considered FW by FAO (2011) and Lipinski et al. (2013) but not by Quested & Johnson (WRAP) (2009) and FUSIONS (2014). The distinction between planned and unplanned non-food use is ambiguous and imprecise: some farmers may not plan in advance how much of their product is going to be directed for human consumption and how much for other use, and they would simply use for animal feeding what could not be sold for human consumption. On the other hand, it is unreasonable to consider a material as waste when it is used for its original intended application, e.g. food that was grown for animal feeding and is used for that purpose should not be considered FW.

Food sent for animal feeding or synthesis of bio-products is not considered FW by Quested & Johnson (WRAP) (2009) and FUSIONS (2014). Furthermore, FAO (2011) and Lipinski et al. (2013) does not consider those materials as FW when animal feeding or synthesis of bio-products were their planned use. However, the value obtained from the application of any of these management alternatives to FW clearly differs from the potential use of food for human consumption, therefore Stuart (2009) considers animal feeding and bio-products synthesis as FW.

The Figure 7-3 summarises the most important differences in the definition of 'food waste' by the most relevant organisations as explained in the previous paragraphs.

It must be pointed out that FAO published another report in 2014 in which the definitions provided were more specific, particularly at defining the beginning and end of the FSC. Besides that, the main difference between FAO (2011) and FAO (2014a) is that the latter considers 'food waste' as a part of the broader concept 'food loss', although it keep defining both in one single concept named 'food loss and waste' (FLW). It must also be considered that FAO (2011) has been widely cited in both the grey and academic literature and is considered a key study in the FW area, and in contrast FAO (2014a) has not received much public nor research attention.

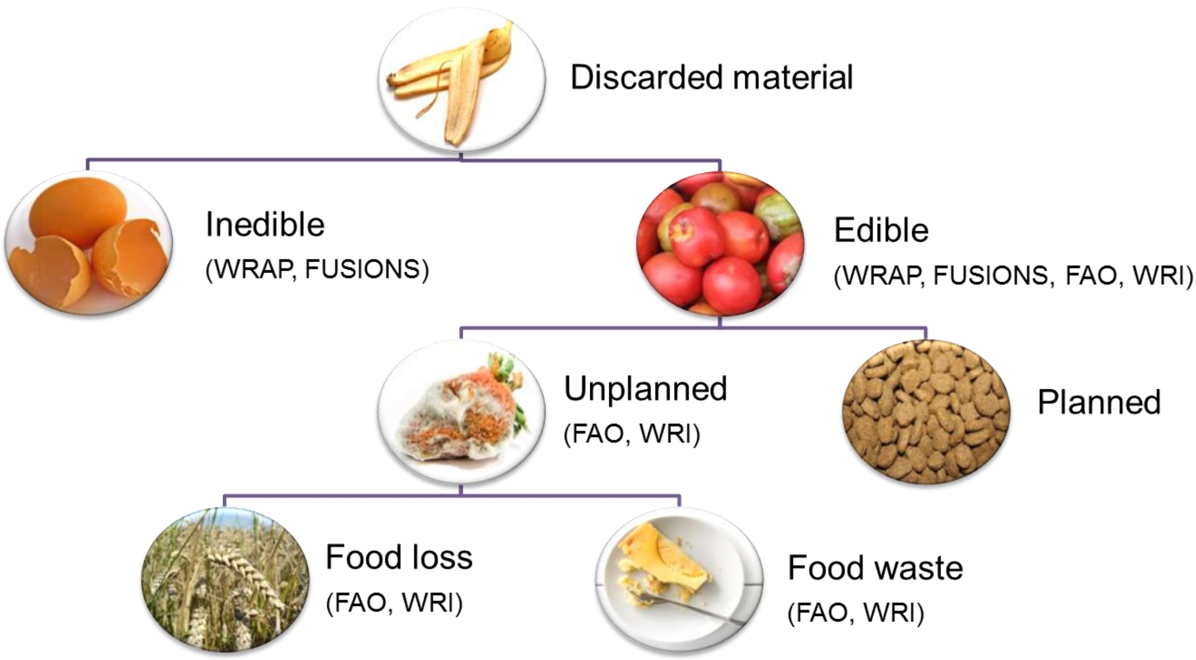


Figure 7-3. Different aspects included in the definition of 'food waste' according to FAO (2011), Lipinski et al. (WRI) (2013), Quested & Johnson (WRAP) (2009) and FUSIONS (2014)

In addition to this, the Food Loss + Waste Protocol published in 2016 a momentous Reporting Standard in which the concept of FLW ('food loss and waste') is used for the sake of simplicity, highlighting that the users of the standard should decide themselves the exact definition to use, based on their quantification goals (Food Loss + Waste Protocol 2016). The reporting standard, namely FLW Standard, considers food (and therefore FW) as the substances intended for human consumption only, and excludes materials such as cosmetics, tobacco, or substances used only as drugs. It does not include in its FW definition processing agents used along the FSC, e.g. water to clean or cook raw materials in factories or at home, nor packaging materials. On the other hand, it includes inedible parts of the food and food that was fit for human consumption but was sent for animal feeding instead. The authors of the Food Loss + Waste Protocol include members of FAO, WRI, FUSIONS, UNEP and WRAP, amongst others.

Eriksson & Spångberg (2017) emphasised the importance of harmonising different definitions and methods to measure FW. Chaboud & Daviron (2017) also identified the lack of consistency amongst FW definitions and developed a framework of analysis, concluding that a focus on the end use of FW is needed.

Based on the reasons described in this section, the following definition of FW is proposed and used throughout the rest of this thesis:

Food waste is any food material (including its inedible parts) originally intended to be used to feed humans and not ultimately sold as planned for human consumption by the food business under consideration

This definition is unambiguous and it can be applied to every stage of the FSC up to the consumer level, and to companies, cities and regions in any area of the world.

The following materials are included in the definition of FW proposed and are therefore considered in the rest of the thesis:

1. Drink waste, which is categorised as FW, since drinks are included in the definition of food (Section 7.2.2). However, water is considered FW only when it is a component of a food or drink composed of different ingredients, e.g. fruit, juice, beer. Bottled water, or wastewater generated from manufacturing activities is not included in the definition.

2. Inedible parts of food (e.g. egg shells and meat bones), since they are an important component of a food material that needs management, and the difficulty of sorting edible and inedible food materials. Inedible parts of food must be associated with edible parts to be considered FW, e.g. inedible skins from some fruits are FW, but stones accidentally collected during the harvesting process are not FW.
3. Food materials which are technically edible, but are considered inedible by the consumers of the geographical area under consideration. For instance, some types of offal are consumed in some countries but not in others. The 'inedibility' of these materials varies amongst consumers and can also change over time. It is affected by factors such as price and local culture.
4. Food materials sent to animal feeding when they were originally intended to be used for human consumption.
5. Food materials used for synthesis of bio-products or any industrial application, when they were originally intended to be used for human consumption.
6. Food redistributed with the help of charities and food banks and consumed by people, when it was originally intended to be sold for human consumption. The social value of this solution is high because food is consumed by people in need or is used in charitable activities, such as fundraising or raising-awareness events. However, this option entails an economic loss to the food company as the food could have been sold and was given away at a lower price, commonly for free. It is important to note that, although from a biological and legal perspective this material is not FW, it is considered FW in this thesis only due to its associated economic loss.

On the other hand, the following considerations fall out of the scope of this research and are not included in the definition of FW:

1. Over-consumption, understood as the gap between the energy value and nutrient content of the food consumed and the energy value and nutrient content needed, which is considered a type of FW by some authors (e.g. Smil (2004)), since over-consumption and obesity are serious problems in a number of countries of the developed world. However, including this aspect in the definition of 'food waste' would significantly complicate the quantification of FW.
2. Food sold and not consumed, since the scope of this research is food companies rather than consumers. When food is sold, food companies get an economic income and meet their ultimate objective (i.e. selling food), whilst the final use of the food product is considered to be the concern of the consumer only. Nevertheless,

although the FWM framework was not designed to be applicable to consumer FW, its existence and significance is recognised and discussed in the thesis.

3. Food grown for other use than for human consumption, such as for animal feeding or any industrial application.
4. Packaging waste, since it is not considered part of the food material. Nevertheless, the framework presented in this chapter allows the assessment of different types of packaged foods.
5. Materials used as ingredients to produce other foods, providing they are consumed in their new food application, e.g. spent yeast from breweries used to produce Marmite®.
6. Substances consumed but not ingested, such as chewing gum and tobacco, since they are not considered food.
7. Harmful substances, which includes products ingested without nutritional value and/or substances which are consumed for recreational purposes, such as recreational drugs, since they are not considered food.
8. Food with lower quality than originally expected, providing they are sold as planned and consumed. Although a decrease in the quality of food is a real problem to tackle (e.g. loss of organoleptic properties), it would be infeasible to measure and quantify food-quality loss in a large scale.

7.2.2 Determination of the boundaries of food systems

The definition of FW proposed can be used to identify FW from various origins, such as farms, food businesses, retailers, cities and countries. Therefore, a clear definition of the food system to be analysed is necessary to delimit the scope of the assessment. Hence, a clear understanding of the types of materials which are considered food (and are prone to become food waste) and types of treatment which are considered 'waste management' is needed.

In order for a material to become FW, it must have been considered 'food' previously. Throughout this thesis, 'food' is defined as any substance or product, whether processed, partially processed or unprocessed, which contains an edible part that is intended to be, or reasonably expected to be ingested by humans. 'Food' includes drinks and any substance, including water, intentionally incorporated into the food during its manufacture, preparation or treatment. This definition is based on the definition provided by The European Parliament and the Council of the European Union (2002).

Table 7-1 proposes specific points in the food systems where different plant and animal materials become food, and when food becomes waste, partially based on previous work by FAO (2014a) and FUSIONS (2014). It should be noted that all materials in the left column will become FW, and therefore fall into one of the categories on the right column, unless they are sold as planned by the food business and consumed by humans. Additionally, Table 7-1 is applicable to food originally intended to be used for human consumption; if food is grown for animal feeding or bioenergy production and is used for those purposes it is not considered FW, as explained in Section 7.2.1. It can be assumed that materials becoming food are entering the food system under consideration, and foods becoming waste are leaving the food system. This thesis analyses materials leaving the food system, i.e. FW.

Table 7-1. Situations in the food systems when a material becomes food, and when food becomes food waste

Material becoming food
Crop is mature for harvest
Fruit is mature for harvest
Animal is ready for slaughter
Wild animal is caught or killed
Milk is drawn from an animal
Eggs are laid by the bird
Fish is caught in the net/on the hook
Fish from fish farm is mature
Any other material which is ready to be processed for human consumption (excluding non-ingested materials and harmful substances, as explained in Section 7.2.1)
Food becoming food waste
Ploughed back into ground
Not harvested
Discarded at sea
Sold at a lower price than originally intended (e.g. to a redistributor of surplus products)
Redistributed for charitable purposes
Fed to animals
Processed to produce bio-materials
Used for industrial applications (such as rendering)
Microbiologically digested (including anaerobic digestion and composting)
Incinerated (with or without energy recovery)
Landspread
Made into briquettes and used in stoves
Flushed down the sewer or to a controlled water course
Landfilled
Littered / disposed of by open dumping or fly tipping

7.3 Identification of types of food waste

A deep understanding of the different types of FW helps to identify poor practices in FWM. Additionally, in the case of the food industry, identifying the point in the production line where FW was generated can also aid in the implementation of a plan to reduce or manage it. For instance, FW generated towards the end of the production line has associated higher economic and environmental costs, which should be taken into consideration when planning how to tackle FW in the manufacturing plant. This section introduces a terminology proposed by the author to describe FW types depending on their location in the manufacturing chain.

The following types of food material that are prone to become FW have been recognised: raw material, unprepared ingredient, prepared ingredient, incomplete food, unprocessed food, processed food and final food product. The identification of food materials was undertaken based on the recognition of standard processes used in food manufacturing: arrival of raw material, preparation and mixing of ingredients, processing, packaging, storage and despatch. A definition of these food materials can be found below:

1. **Raw material**: food product as it leaves the production stage that must be processed before being sold to the final consumer. Raw materials become FW if they are spoilt, expired, damaged during transportation or storage, or do not meet the quality standards required. By-products generated from raw materials are also FW (e.g. branches and leaves from fruits that arrive to the food company).
2. **Unprepared ingredient**: ingredients that have to undergo some process before they are ready to be mixed with other ingredients, or to be packaged if it is to be sold as a single food product. Unprepared ingredients become FW if they are spoilt, expired or damaged during preparation. By-products generated from unprepared ingredients are also FW (e.g. skins from some fruits).
3. **Prepared ingredient**: ingredients ready to be mixed with other ingredients, or ready to be packaged if is to be sold as a single food product. Prepared ingredients become FW if they are spoilt, expired or damaged during preparation.
4. **Incomplete food**: food product made of different food materials that does not contain all the ingredients of the final food product. Incomplete foods become FW if they are spoilt, expired or damaged during processing. By-products generated from incomplete foods are also FW (e.g. residue from a filtration process when manufacturing a juice made of different fruits).
5. **Unprocessed food**: food that has to undergo some processing before it has the required properties required by the final consumer. Unprocessed foods become FW if

they are spoilt, expired or damaged during processing. By-products generated from incomplete foods are also FW (e.g. yeast from fermentation and maturation processes in breweries).

6. **Processed food**: food with the same properties to those required by the final consumer at the point of sale, but unpackaged. Processed foods become FW if they are spoilt, expired, damaged during packaging or do not meet the quality standards required.
7. **Final food product**: processed and packaged food ready to be sold. The final food product becomes FW if it is spoilt, expired, if it cannot be sold due to a lack of buyers or if unacceptable errors in the product or processes involved are found.

In the Figure 7-4, the production processes and different types of food using this terminology have been exampled with the production of a pizza. It is worth noting that the order of the processes may vary slightly among different food products and manufacturing sites. For instance, when manufacturing some types of milkshake there can be food processing (e.g. heat treatment) after packaging (i.e. bottling).

7.4 Qualitative parameters to classify food waste

Once the boundaries of the food system to be analysed have been set, and all types of FWs have been identified according to the definition of FW provided in Section 7.2.1, FW must be categorised to better understand its properties. The aim of such a categorisation is to provide support for an improved selection of solutions to manage FW, prioritising FWMSs with sound sustainability performance (i.e. maximising economic, environmental and social benefits whilst reducing their impacts). As explained in Section 5.2, a comprehensive and exhaustive categorisation of all types of FW to support FWM does not exist yet. This section presents a novel FW categorisation, in which some of the food categories used in Section 5.2 are used, e.g. edible/inedible; some categories are new, e.g. processed/unprocessed; and some already exist but slight changes in their meaning are proposed, e.g. eatable/uneatable.

The categorisation proposed in this thesis is based on nine qualitative parameters as introduced in Garcia-Garcia et al. (2015) (Appendix 2) and explained in more detail in Garcia-Garcia et al. (2016) (Appendix 6). The nine parameters used are shown in Figure 7-5. The categorisation process can be applied to all types of FW as defined in Section 7.2.1. It is based on nine characteristics that the author considers most important in order to prioritise the most sustainable FWMS for each type of FW. The selection of characteristics was based on the four criteria explained in the next page.

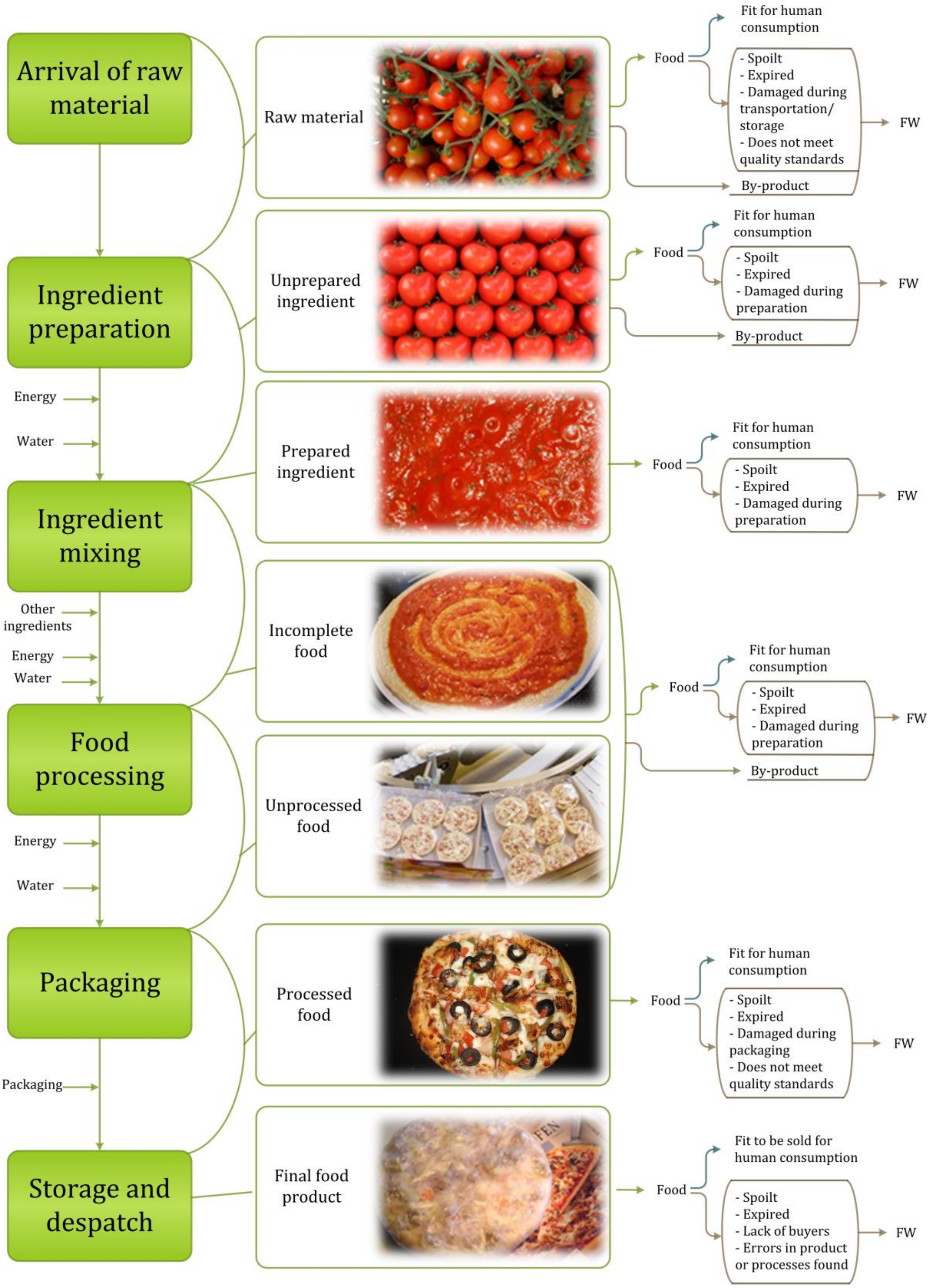


Figure 7-4. Types of food material at different phases of a food manufacturing site

1. The characteristics must be qualitative and easy to assess, generally at a glance.
2. The characteristics must be specific and only one out of two or three parameters must be selected in each stage of the categorisation process.
3. The characteristics must be determinative and non-redundant to discriminate between different solutions to manage FW and select more sustainable FWMSs.
4. The characteristics must be applicable to all types of FW and non-specific to any one food category.

The evaluation of these nine characteristics provides a systematic classification of the different types of FW that enables a more appropriate selection amongst the available FWMSs. The analysis of each stage has been simplified in a way that there are only two or three types of FW in each step of the categorisation process. Additionally, the parameters have been designed to simplify the analysis, and consequently in most cases the assessment can be completed through visual inspection of the FW with no technical knowledge required. The different qualitative parameters at each stage of the categorisation process are described in the following sections.

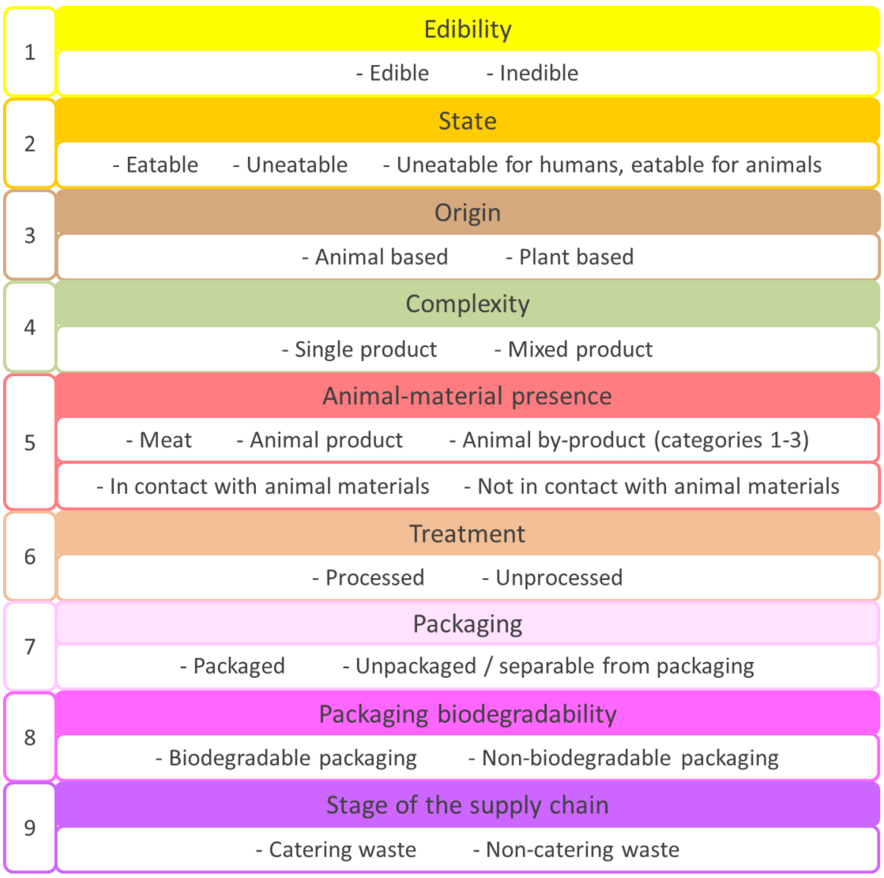


Figure 7-5. Qualitative parameters to categorise FW and the nine-stage FW categorisation

7.4.1 Edibility

A food product is edible if it is or has been expected to be consumed by humans at any point during its life cycle. Under all other conditions the product is inedible (e.g. some fruit skins, meat bones and some vegetable stalks). When the product is edible from a biological point of view, but there is no consumer demand for it (e.g. chicken feet), it is considered inedible in this scheme, as its reallocation for human consumption is not possible. Consequently, the edibility of some FWs can vary over time and geographical area considered. Various food products still contain inedible parts when they reach the point of sale (e.g. a banana and its peel); in these cases the food products are considered edible.

7.4.2 State

'State' must be assessed for edible products only. The food product is eatable when it has not lost the required properties to be sold and to be fit for human consumption at the moment of its management as FW. Under other circumstances the product is considered uneatable. If the food has not lost those properties, but it still requires further processing in the industry before being sold and consumed, it is classified as eatable and unprocessed (see parameter 'treatment' in Section 7.4.6). A food product can become uneatable by being damaged at different points of the FSC (e.g. overcooked during its manufacture, spilled during its distribution), becoming spoilt (e.g. due to leaving the cold chain) or passing its use-by date. If a product contains both eatable and uneatable parts and it is going to be managed as a whole, it must be considered uneatable, since if a part of the food product is not fit for human consumption, the entire product should be discarded. When the product is eatable from a biological point of view, there may still be ethical issues that can lead to classify it as uneatable to restrict its usage for human consumption, for instance to prevent using surplus alcoholic drinks for redistribution to charities, or products that do not meet the minimum quality standards to an acceptable required level. A third type of FW in this categorisation stage includes products which are uneatable for humans because of safety concerns, but still fit for animal feeding (e.g. fallen from conveyor belts during manufacturing and thus discarded for human consumption).

7.4.3 Origin

The food product is animal based if it was produced by an animal (e.g. dairy products, eggs, honey) or using parts of an animal (e.g. meat, which includes fish). Otherwise the product is plant based, which includes all plant-based products and all materials which cannot be considered animal-based materials, such as salt and fungi. When the product contains both animal and plant-based materials (e.g. convenience foods), it must be classified according to its main ingredient, which is the predominant ingredient by mass. When the main ingredient is plant based, but there are some animal-based materials, the product is also classified as a mixed product (as explained in the next categorisation stage).

7.4.4 Complexity

This characteristic is required for plant-based products exclusively. A single product is formed of only one type of ingredient and it has not been in contact with other food material. In any other circumstances the product is mixed.

7.4.5 Animal-material presence

When the product is animal based, it must be further categorised as meat (which includes fish), animal product (i.e. a product produced by animals) or by-product from an animal carcass (ABP) not intended for human consumption (e.g. by-products from slaughterhouses). In the last case, the FW should be additionally classified according to European regulations into Category 1, 2 or 3 (The European Parliament and the Council of the European Union 2009a). Plant-based mixed products must be assessed in order to evaluate whether the product contains or has been in contact with animal-based material.

7.4.6 Treatment

A product is considered processed when it has the same properties as the final food product to be sold to the consumer. This occurs when either the food product has completed the manufacturing process, e.g. a ready meal, or the food does not need any processing before being distributed, e.g. most fresh fruits and vegetables. If the food still needs any treatment at the moment of its management as FW it is considered unprocessed. Consequently, only edible and eatable FW needs to be assessed in this stage.

7.4.7 Packaging

A product is unpackaged if it is not contained in any packaging material. If the product is packaged but there is an available technology for the company to unpack and separate the FW from its packaging, the product can be considered unpackaged. Under other circumstances the product is considered packaged.

7.4.8 Packaging biodegradability

Obviously, this characteristic must be assessed for packaged foods only. Commonly, a material is biodegradable if it can be digested by microorganisms, although the process may last for several months or even years. Hence, in this thesis biodegradable packaging refers to that made of materials which have been tested and received a certificate of being “suitable for anaerobic digestion” or “compostable" (e.g. ‘OK compost’ logo and ‘DIN CERTCO’ logo). Biodegradable packaging is generally made of paper, cardboard, bioplastics, or any plant-based product. Non-biodegradable packaging is usually composed of plastic, glass or metal.

7.4.9 Stage of the supply chain

Catering waste includes domestic waste and waste from the food service sector (i.e. staff catering, healthcare, education, services, restaurants, quick service restaurants, pubs, hotels and leisure). As opposed to catering waste, non-catering waste is generated in earlier stages of the FSC (i.e. at farm, manufacturing, distribution or retail level).

7.4.10 Applicability of the FW categorisation

The FW categorisation explained in this section is applicable to all types of FW. Although it is easy to use, since it is based on simple, qualitative characteristics, it is also determinative to select the most sustainable FWMS, as explained in the next section.

7.5 A methodology to find the most sustainable waste management solution for each type of food waste

The assessment of the nine stages of the FW categorisation explained in the previous section, and the consequent determination of nine characteristics, is the starting point to select the most sustainable FWMS. Following the nine-stage categorisation, each combination of nine FW characteristics has one most suitable FWMS associated with it. This section proposes and ranks a set of FWMSs for the different FW types identified following the nine-stage FW categorisation, as described by Garcia-Garcia et al. (2016) (Appendix 6).

7.5.1 Selection of the version of the FWH to classify FWMSs

The waste hierarchy applied to food products (FWH) is an appropriate tool to classify the different options to manage FW based on their sustainability performance, i.e. environmental, social and economic implications of FWM (Papargyropoulou et al. 2014, Manfredi & Cristobal 2016). The specific order of the different options in the hierarchy (i.e. the preference of some options against others) is debatable. For instance, some authors place anaerobic digestion and/or composting in the recovery section (e.g. IGD (n.d.), Defra (2011b), Defra (2011c)); on the other hand, Adenso-Diaz & Mena (2014) and WRAP (2014), amongst others, include them in the recycling section. Additionally, Rossi et al. (2015) demonstrated that in certain cases thermal treatments with energy recovery can be more environmentally friendly than composting. Although there are several slightly different adaptations of the FWH, the most recent versions are usually based on the Waste Framework Directive 2008/98/EC (The European Parliament and the Council of the European Union 2008).

The version of the FWH to be used in this thesis is presented in Figure 7-6. It has been designed after completing an exhaustive review of existing FWHs, and based on previous work by Defra et al. (2011), Adenso-Diaz & Mena (2014), Papargyropoulou et al. (2014) and Eriksson et al. (2015). When a disagreement existed between different sources with regard to the order of two FWMSs (e.g. anaerobic digestion and composting), the most common order reported in the literature was decided. The final objective of the FWH is to prioritise solutions which provide not only better environmental performance, but also economic and social results. Balancing these three sustainability pillars is intricate, since some FWMSs provide better performance for one of the pillars but poorer results in the others. The FWH presented in Figure 7-6 takes this into consideration and aims at presenting the order of FWMSs based on overall performance. For instance, redistribution for human consumption usually has poorer economic performance than other options lower down the FWH, but its optimal social performance justifies placing in the second position of the FWH.

Five FWMSs (redistribution for human consumption, animal feeding, anaerobic digestion, composting and thermal treatment with energy recovery) are highlighted because they are the only solutions considered in the rest of the thesis. This is justified in Section 7.5.1.6, which discusses FWMSs that have not been included in the procedure to select sustainable FWMSs, namely Food Waste Management Decision Tree (FWMDT), which is presented in section 7.5.2. A description of the FWMSs evaluated and the associated types of FW can also be found in the following pages, along with a justification of their position in the FWH.

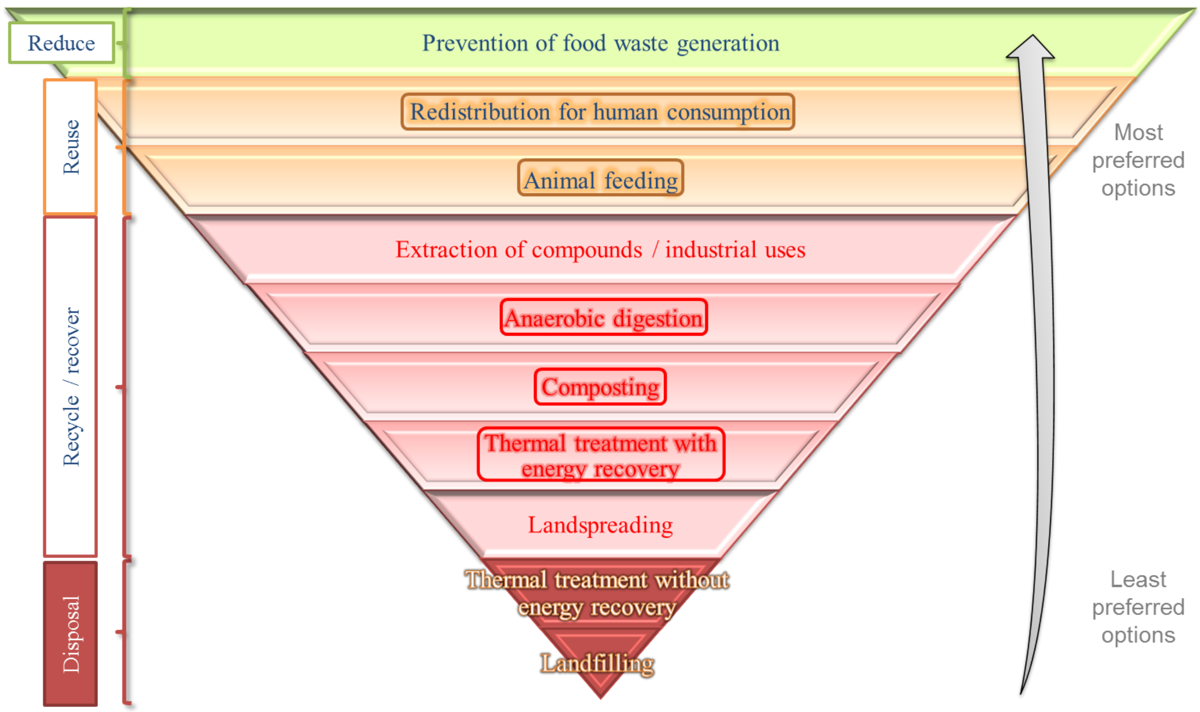


Figure 7-6. Waste hierarchy for surplus food and FW

7.5.1.1 Redistribution for human consumption

When FW cannot be prevented, redistribution for human consumption is the optimal FWMS, since food is used as originally intended to feed people. This provides an optimal social outcome, due to the social value of feeding people in need or using FW in charitable activities, such as fundraising or raising-awareness events. Additionally, its environmental performance is high since FW is consumed and therefore a waste management treatment is not necessary. Preparing the FW (e.g. washing, cooking) may be necessary prior to serving the food, and this causes an environmental impact (e.g. use of energy and water), although this FW would substitute other food that would also need to be prepared to be used for human consumption. Therefore, the environmental impact of preparing the food can be considered to be zero. On the other hand, the economic result may be not the best compared to other options in the FWH, because food companies generally receive a low or no income from this FWMS. Overall, the optimal social outcome and the very good environmental implication compensate by far the rather low economic result of redistributing FW for human consumption. Generally, charities and food banks are in charge of collecting and distributing surplus food for people in need. Philanthropic organisations organise fundraising or raising-awareness events where FW can be used to feed people.

This alternative is accessible for edible, eatable and processed products, as defined in Section 7.4. Processed food does not necessarily mean that the final product was fully processed as initially planned by the food business, e.g. surplus potatoes for the preparation of chips for convenience foods can be redistributed if they still are fit for distribution and human consumption (e.g. they have not yet been peeled) and comply with legislation. In this case the potatoes are defined as processed because they are as sold to final consumers.

Redistribution for human consumption must meet the following European legislation: General Food Law (The European Parliament and the Council of the European Union 2002), Food Hygiene Package (The European Parliament and the Council of the European Union 2004a, The European Parliament and the Council of the European Union 2004b, The European Parliament and the Council of the European Union 2004c, The European Parliament and the Council of the European Union 2004d), the Regulation (EU) No 1169/2011 (The European Parliament and the Council of the European Union 2011), and the Tax legislation (The Council of the European Union 2006), as explained by O'Connor et al. (2014). An extensive analysis of the situation of food banks and food donation in the UK was carried out by Downing et al. (2014).

7.5.1.2 Animal feeding

This is the most suitable FWMS for FW not fit for human consumption but apt for animal feeding. Its social benefit is lower than for redistribution, since FW is used to feed animals and not humans. Its environmental performance can be considered as good as that of redistribution, since a waste management treatment is not necessary and the use of FW for animal feeding substitutes the use of other food materials in animal feeds. The economic result of animal feeding is similar or better than that of redistribution for human consumption, since food companies may give away the FW for free or sell it and receive an economic income in certain cases. In either way, its significantly lower social benefit justifies placing it lower than redistribution in the FWH. Yet, its positive social and environmental implications, along with a neutral or also positive economic outcome, prove animal feeding is more sustainable than other FWMSs lower down in the FWH.

In this analysis only animals from the FSC are considered for animal feeding (farmed animals such as cattle, swine, sheep, poultry and fish). Pets and non-ruminant zoo animals are excluded, following guidelines explained at Gov.uk (2014e). In order to be used for animal feeding, products must be eatable or uneatable for humans but eatable for animals, unpackaged or separable from packaging, and non-catering waste. Inedible, plant based, single product, non-catering waste can be used for animal feeding depending on the type of FW: this particular case must be assessed for each type of FW independently. When the FW has been categorised as mixed, it must be either not in contact with or containing meat, by-products from animal bodies or raw eggs if it is eatable, or not in contact with or containing animal-based products if it is inedible or uneatable for humans but eatable for animals. Mixed waste containing animal products from manufacturers is suitable for animal feeding when the animal product is not the main ingredient. Meat and plant-based products containing meat cannot be sent for animal feeding. Eggs, egg products and plant-based products containing eggs must have been generated at the production or manufacturing stage and follow specific treatments when used for animal feeding. Milk and dairy products can be used for animal feeding providing they are processed (the processing needed is similar to that for human consumption), or unprocessed under UK rules if the farm is a registered milk processing establishment. Inedible, animal based, category 3 FW can be used for animal feeding only under the conditions listed in the FWMDT (Figure 7-10). According to European regulations (explained below), all types of category 3 animal by-products can be used in animal feed except hides, skins, hooves, feathers, wool, horns, hair, fur, adipose tissue and catering waste. However, UK regulations are stricter than European legislation and thus this has been used to develop the FWMDT. It must be noted that although some category 3 animal by-products are technically edible, they are not intended for human consumption. In any case, they must be not spoilt in order to be used for animal feeding, and in most cases they must be processed following specific requirements before being utilised. If a FW contains different categories of animal by-products, it must be treated following the requirements of the material with the highest risk (category 1 has the highest risk and category 3 the lowest).

The following sources have been used to develop the FWMDT and must be consulted when using animal by-products to prepare animal feeds: European regulations (European Commission 2005a, The European Parliament and the Council of the European Union 2009a, European Commission 2011) and UK legislation (The Secretary of State 2013). Any company or person donating or receiving food for animal feeding must also be registered under the specific activity code with the local Trading Standards office under the EU Feed Hygiene Regulations (European Commission 2005b). Useful guidance information to produce animal feed in the UK can be found at Defra (2011a), Gov.uk (2014e). Further information on additional legislation that applies to work with animal by-products can be found at Gov.uk (2014b) and Gov.uk (2014g) for milk products. Eggs must be treated in a processing facility under national rules (Gov.uk 2014d). The following additional legislation for animal feeding has also been consulted: European regulations (European Commission (2002), The European Parliament and the Council of the European Union (2003), The European Parliament and the Council of the European Union (2009b)) and regulations in England (The Secretary of State 2010b). General guidance and more information on animal feeds have been collected by the Food Standards Agency (n.d.) and the Food Standards Agency (2014).

7.5.1.3 Anaerobic digestion

Anaerobic digestion (AD) does not provide a significant positive social outcome as redistribution and animal feeding do, since FW is not consumed and therefore is not used as food, consequently lowering its value. This loss of social value causes a lower sustainability performance of AD compared to redistribution and animal feeding. The process of AD also creates an environmental impact, e.g. emission of greenhouse gases. Nevertheless, since this FWMS allows recovering energy from FW, AD has associated an overall positive or negative environmental implication depending on the energy source it can be considered it substitutes, for instance fuel-based energy or renewable sources. In terms of economic results, it may also be positive or negative for the food business depending on who processes the FW. Generally, if the food manufacturer sends the FW to a waste processing facility to be anaerobically digested, the food manufacturer would need to pay a fee (namely gate fee). Otherwise, if the company that generates the FW manages it with AD, a positive economic result can be achieved, selling biogas or electricity produced. Both environmental and economic results are generally better than those obtained with composting or thermal treatment with energy recovery, which justifies its higher position in the FWH.

AD can be used with all types of FW except category 1 animal by-products and packaged waste (i.e. non-separable from packaging) in a non-biodegradable packaging. Category 3 animal by-products must be pasteurised; the particle size of category 2 animal by-products must be 50 mm or smaller, and its core must have reached a temperature of 133 °C for at least 20 minutes without interruption at an absolute pressure of at least 3 bar (The European Parliament and the Council of the European Union 2009a, The Secretary of State 2013, Gov.uk 2014f). In the UK, AD plants must comply with regulations with regard to environmental protection, animal by-products, duty of care, health and safety and waste handling (more information about the different legal requirements can be found at Biogas-info.co.uk (n.d.)).

7.5.1.4 Composting

Composting provides a similar social value than AD. Its environmental performance is significantly less favourable than for AD (Defra 2011b, Defra et al. 2011, Fisher et al. 2013), but better than for thermal treatments with energy recovery, since compost is used to enhance the quality of the soil and composting generates low emissions compared to thermal processes. Similarly than with AD, the economic outcome depends on who processes the FW: if it is sent to be composted in a waste processing facility the economic outcome would be negative for the food manufacturer; if it is processed by the company that generates the FW, compost can be sold and an economic income would be obtained.

The types of FW suitable for composting are the same as for AD: all FW except category 1 animal by-products and packaged waste (i.e. non-separable from packaging) in non-biodegradable packaging. Composting category 2 animal by-products is possible if the process is carried out under the following regulations: The European Parliament and the Council of the European Union (2009a), The Secretary of State (2013). In-vessel composting (i.e. composting in closed vessels) must be used when FW contains or has been in contact with any animal-based material (WRAP 2011, Gov.uk 2014f), because these materials can attract vermin. Further guidance for the composting of waste can be found in (WRAP n.d.).

7.5.1.5 Thermal treatment with energy recovery

Thermal treatments with energy recovery are the least sustainable option from the five FWMSs discussed, due to their poor social (Defra 2013b) and environmental performance (FAO 2013b). Similarly than with AD and composting, thermal treatments with energy recovery can cause an economic cost to the food manufacturer if FW is processed elsewhere or an economic benefit for the waste processor if enough energy is obtained from the thermal treatment.

This option can be applied to every type of FW; nevertheless its use must be minimized as it provides small benefits compared to the impacts generated. Thermal treatments with energy recovery include incineration, pyrolysis and gasification, as explained in Section 4.3.5. They are the only alternatives available to treat packaged food (i.e. non-separable from packaging) in non-biodegradable packaging, except the cases when the product is also edible, eatable and processed, and therefore it can be redistributed for human consumption. As this type of FW is the final packaged product it would usually be generated in the last stages of the FSC, particularly at retailing and consumer level (which is usually mixed with municipal solid waste). Due to the mainly high water content of FW, a great quantity of energy is needed to treat FW with this FWMS, and therefore this solution may be useful and give an energy return on investment when treating dry FW (e.g. bread and pastries) or FW mixed with other materials, such as in municipal solid waste. Thermal treatments with energy recovery are also the most appropriate FWMS to treat category 1 animal by-products, which in some cases, need to be processed by pressure sterilisation (The European Parliament and the Council of the European Union 2009a, The Secretary of State 2013).

Useful information on incineration of municipal solid waste was collected by Defra (2013b). Data with regard to technologies and emissions from waste incineration plants have been collected in the Best Available Techniques for Waste Incineration (European Commission 2006c).

7.5.1.6 FWMSs from the FWH not included in the FWMDT

The development of a categorisation that covers all types of FW is arduous not only due to the number of FW types and their variety, but also because there are numerous alternatives for FWM. Some of the FWMSs have been grouped in Figure 7-6, for instance all processes for extracting substances from all types of FW are included in the alternative 'extraction of compounds / industrial uses'. This is because there are dozens of chemical and physical routes to obtain bio-compounds from FW, and also numerous possibilities to use different types of FW for industrial applications such as removal of pollutants from wastewater. It is therefore infeasible to consider all these options explicitly for all the FW categories. Furthermore, extraction of compounds and industrial uses are generally considered more sustainable FWMSs than other recycling, recovery and disposal options from the FWH, principally due to their potentially high economic benefit. Consequently, in all cases when there are FWMSs other than redistribution and animal feeding suggested in the FWMDT, a targeted study for each type of FW must be carried out in order to find opportunities to extract compounds of interest or industrial applications, before considering options lower down in the FWH. The use of a bespoke FWH for each type of FW identified would be an ideal solution, as explained in Section 4.3.7.

Additionally, prevention of FW generation is not included in the FWMDT because it is out of the scope of this thesis, and also this option would be always prioritised, as it is at the top of the FWH and could potentially be applied to all types of edible FWs. The option of prevention includes reducing the quantity of FW generated in the production line and identifying alternative uses of products for human consumption, e.g. a misshapen vegetable that can be used to prepare a ready meal. In these cases the product must be reprocessed, and it would not be considered FW according to the definition provided in Section 7.2.1, thus falling out of the scope of this research. If instead it is directly consumed by humans without further processing the solution considered would have been redistribution, although this gives a smaller economic benefit to the food company than selling it at its regular price, and consequently the food would be considered FW. In this thesis it is assumed that all prevention steps have been taken to minimise FW generation, but nevertheless FW is created and an optimisation of its management is required.

Landspreading can be used with the majority of types of FW, but according to the version of the FWH used (Figure 7-6) this FWMS is less beneficial than composting. As both alternatives can be used to treat the same types of FWs, landspreading has not been further considered in this work and only composting has been examined.

The last two FWMSs, landfilling and thermal treatment without energy recovery, are not considered in the analysis. Both have a significant environmental impact (Lohri et al. 2015, Calaf-Forn et al. 2014), and they also cause negative economic and social ramifications. In both cases there are always more sustainable FWMSs that can be applied, even if these two alternatives could be potentially used with all types of FW, regardless of their nature.

7.5.2 The Food Waste Management Decision Tree

In order to connect FW with their most sustainable FWMSs from the FWH, the parameters described in Section 7.4 have been firstly used to identify the different types of FW. Each parameter has been assessed and superfluous categories have been eliminated to simplify the assessment (e.g. state for inedible FW). A maximum of three FWMSs have been identified for each type of FW, ensuring that at least one of the FWMS should be available to use. Selected FWMSs have been ranked according to their sustainability performance using the FWH (Figure 7-6). All FWMSs proposed are in compliance with UK and European regulations. The result of this assessment has been represented in a diagram, namely Food Waste Management Decision Tree (FWMDT), which helps with analysing FW using the parameters proposed. The FWMDT has been divided into four parts for display purposes and can be seen in Figure 7-7 (edible, eatable animal-based FW), Figure 7-8 (edible, eatable, plant-based FW), Figure 7-9 (edible, uneatable FW) and Figure 7-10 (inedible and uneatable for humans, eatable for animals FW).

The FWMDT is intended to be easy to use and determinative for selection of the optimal FWMS, taking into account current legislation and economic, environmental and social ramifications of FWM. It functions as a flowchart: the user starts at the highest level, and selects the parameter that best describes the FW under consideration (e.g. edible or inedible). The user then moves through subsequent levels of the diagram, following the arrows and making further parameter selections. At the bottom the user is presented with a set of FWMSs that differ according to the set of parameters for that FW type.

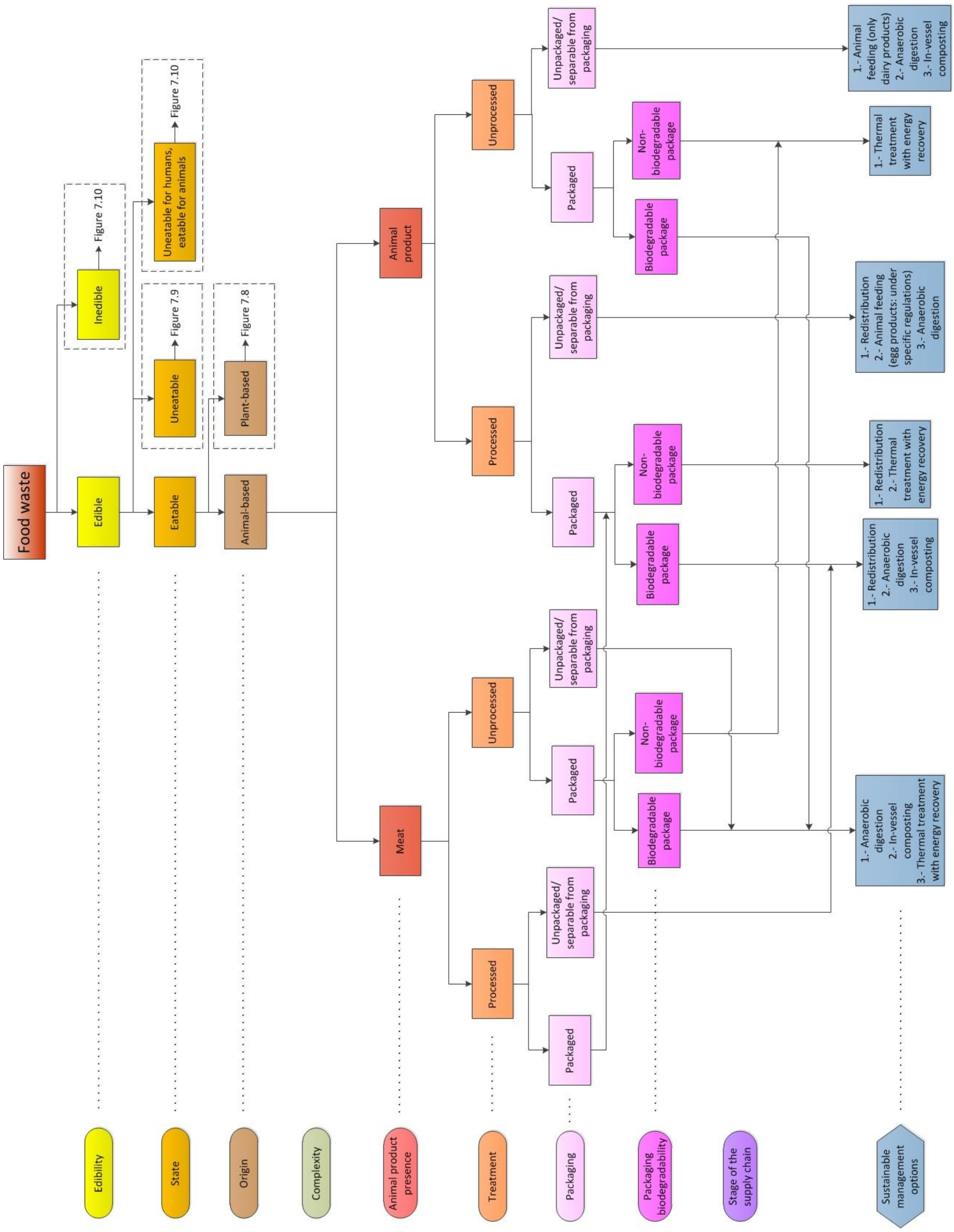


Figure 7-7. The Food Waste Management Decision Tree. Edible, eatable, animal-based FWs and their most sustainable FWMSs

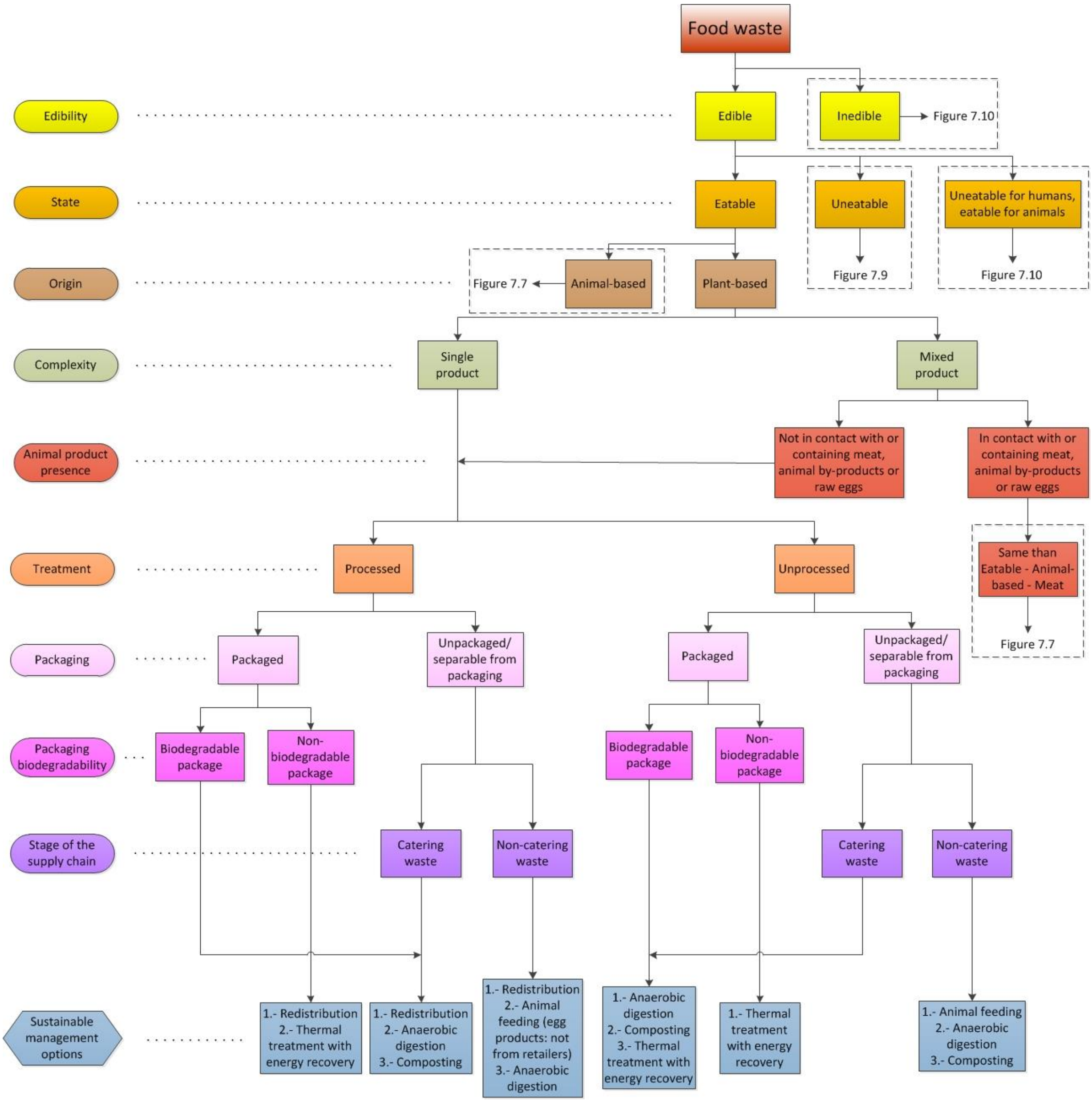


Figure 7-8. The Food Waste Management Decision Tree. Edible, eatable, plant-based FWs and their most sustainable FWMSs

The FW must be broken down for analysis into the same subgroups as for the treatments to be applied, e.g. if a food company generates both animal-based waste and plant-based waste which are collected and treated separately, they must also be assessed independently. However, if a ready-meal manufacturer produces undifferentiated FW composed of both plant and animal products, this must be studied as a whole product. In the latter example, the FW is classified as a mixed product. Separate collection provides the benefit that more targeted management practices can be applied on the different FW streams. When separate collection is not possible, a thorough waste sorting is recommended, although some of the alternatives would not be available then (e.g. plant-based FW that has been in contact with meat cannot be used for animal feeding).

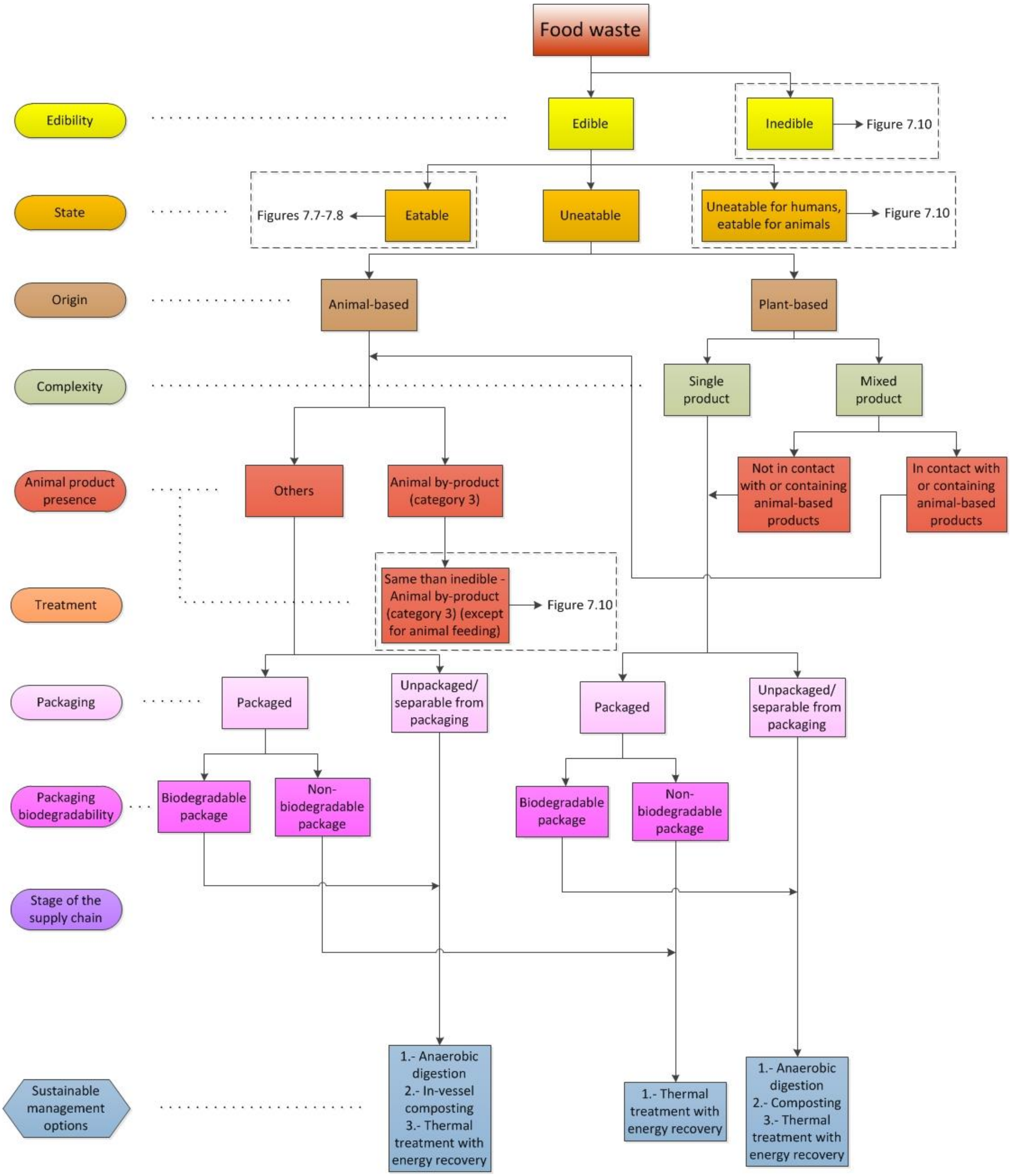


Figure 7-9. The Food Waste Management Decision Tree. Edible, uneatable FWs and their most sustainable FWMSs

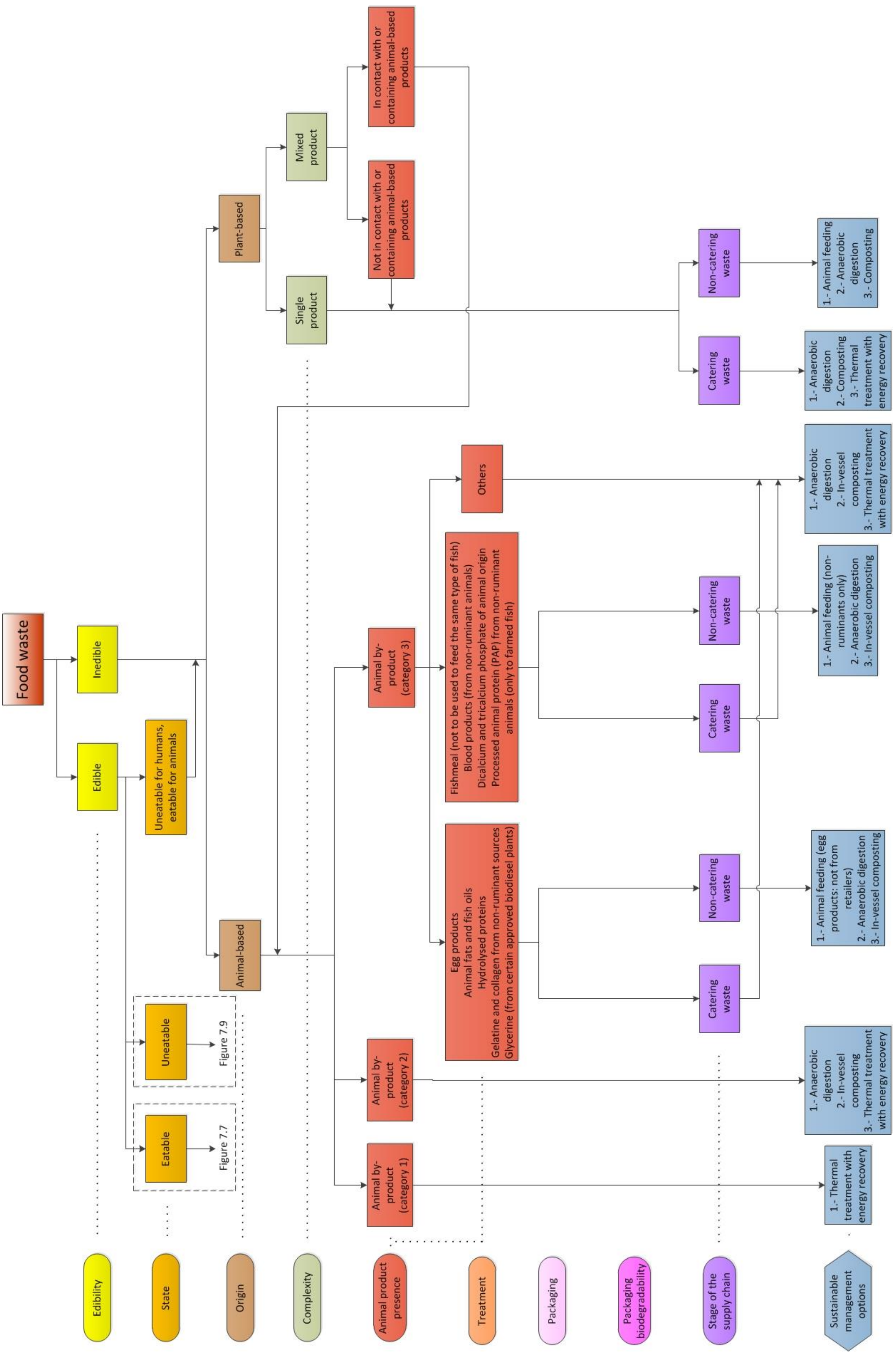


Figure 7-10. The Food Waste Management Decision Tree. Inedible and uneatable for humans, eatable for animals FWs and their most sustainable FWMSs

The FWMDT was designed as far as possible to embody the categories and parameters described in Section 7.4, but this was not always achievable. For instance, the category animal-material presence includes additional parameters for inedible, animal-based products, as can be seen in Figure 7-10, to comply with European regulations (The European Parliament and the Council of the European Union 2009a).

7.6 Chapter summary

This chapter has introduced a novel FWM framework that can be used as a guidance to identify and assess more sustainable solutions for FWM. In order to keep consistency in this thesis, a comprehensive analysis of prospective aspects to be included in the definition of FW has been completed, and as a consequence a new definition of FW has been proposed, which not only is used throughout the rest of the thesis but can also be used by any researcher or manager of FW. Similarly, the boundaries of the food systems have been defined, delimiting the scope of the research. These definitions provide a basis to identify FW types in a food company. A terminology has been proposed to describe FWs according to their point in the production line where they were generated.

Once the FW has been identified, the next step is to categorise it according to a pre-established criterion. A novel nine-stage FW categorisation based on qualitative parameters has been proposed and described in this chapter. The categorisation is universally applicable and has been used to identify all possible types of FW. This analysis has been utilised to design the Food Waste Management Decision Tree (FWMDT). The most appropriate FWMSs have been identified for each type of FW using the FWMDT, which prioritises the most sustainable FWMSs. The feasibility of using each FWMS from the FWH has been discussed, highlighting constraints due to UK and European legislations and environmental, economic and social ramifications.

CHAPTER 8 QUANTITATIVE ATTRIBUTES TO MODEL FOOD WASTE MANAGEMENT

8.1 Introduction

This chapter presents an analytical process to assess environmental, economic and social implications of FWMSs as the next step of the framework after using the FWMDT. After selecting the most sustainable solution for FWM using the qualitative parameters and methodology described in Chapter 7, there is a need to procure a precise, quantitative estimation of the output generated from managing FW. In order to achieve this, this chapter introduces a series of quantitative attributes to model FWM, which are used to design a Food Waste Management Modelling Procedure (FWMMP). The procedure comprises the determination and analysis of attributes categorised as FW parameters, management and company variables, FWM performance factors and sustainability indicators. The FWMMP can be used as a methodical scheme to identify and assess all information needed to model FWM.

8.2 Overview of the Food Waste Management Modelling Procedure

The FWMMP consists of a systematic methodology to estimate environmental, economic and social implications of FWM, as outlined by Garcia-Garcia et al. (2017) (Appendix 7). The analysis introduced in Chapter 7 (i.e. nine-stage categorisation and FWMDT) can be incorporated in this procedure, as it provides a recommendation of the most sustainable FWMS to manage the FW under consideration. However, as opposed to the FWMDT, the FWMMP uses quantitative attributes to model FWM, which can therefore be useful to accurately estimate a quantitative outcome from managing FW using the FWMS selected by the food company. Additionally, the FWMMP can be used to compare the FWMS selected against other possible alternative solutions, reassuring that the option selected is the most sustainable solution for FWM. It is possible, although expected to be uncommon, that a quantitative assessment with the FWMMP reveals that the solution proposed using the FWMDT is not optimal, and that there is an alternative solution with better sustainability performance. This is unlikely, because it would disagree with the FWH, which, as discussed in Sections 4.3 and 7.5.1, is a reliable way of classifying FWMSs according to their sustainability implications. It is more likely, however, that a company decides to use an alternative solution to the one proposed with the FWMDT if the FWMMP highlights a potential improvement in one specific aspect of FWM of special relevance for the company. For instance, a food manufacturer can decide to sell FW for animal feeding rather than redistributing it to people in need if animal feeding can provide a higher economic benefit to the food business, and despite the option of redistribution to people having an overall better sustainability result. Consequently, the FWMMP can provide more customised and precise results to a food company. Nevertheless, the main drawback of using the FWMMP is the difficulty to collect all data needed and model all possible solutions, as opposed to the simple-to-use FWMDT.

The structure of the FWMMP can be seen in Figure 8-1 and includes four stages, in which the identification and assessment of the following attributes is needed: qualitative (from Section 7.4) and quantitative parameters to evaluate properties of FWs, variables to model FWM processes and status of the company under consideration, factors to assess the performance of FWM practices, and sustainability indicators to analyse ramifications of FWMSs.

A flowchart description of the use and operation of the FWMMP can be found in Figure 8-2. There are three major phases: data collection, data processing and decision making. Data collection must be completed by the user, but data processing and decision making can be implemented in a software tool to automatize and accelerate the procedure. The three major phases to use the FWMMP are explained in the next page.

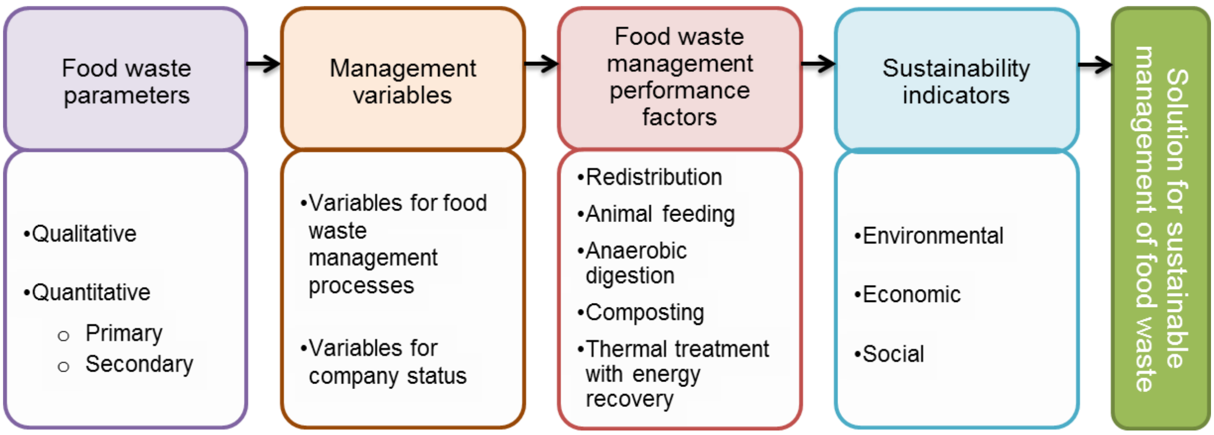


Figure 8-1. Stages of the Food Waste Management Modelling Procedure

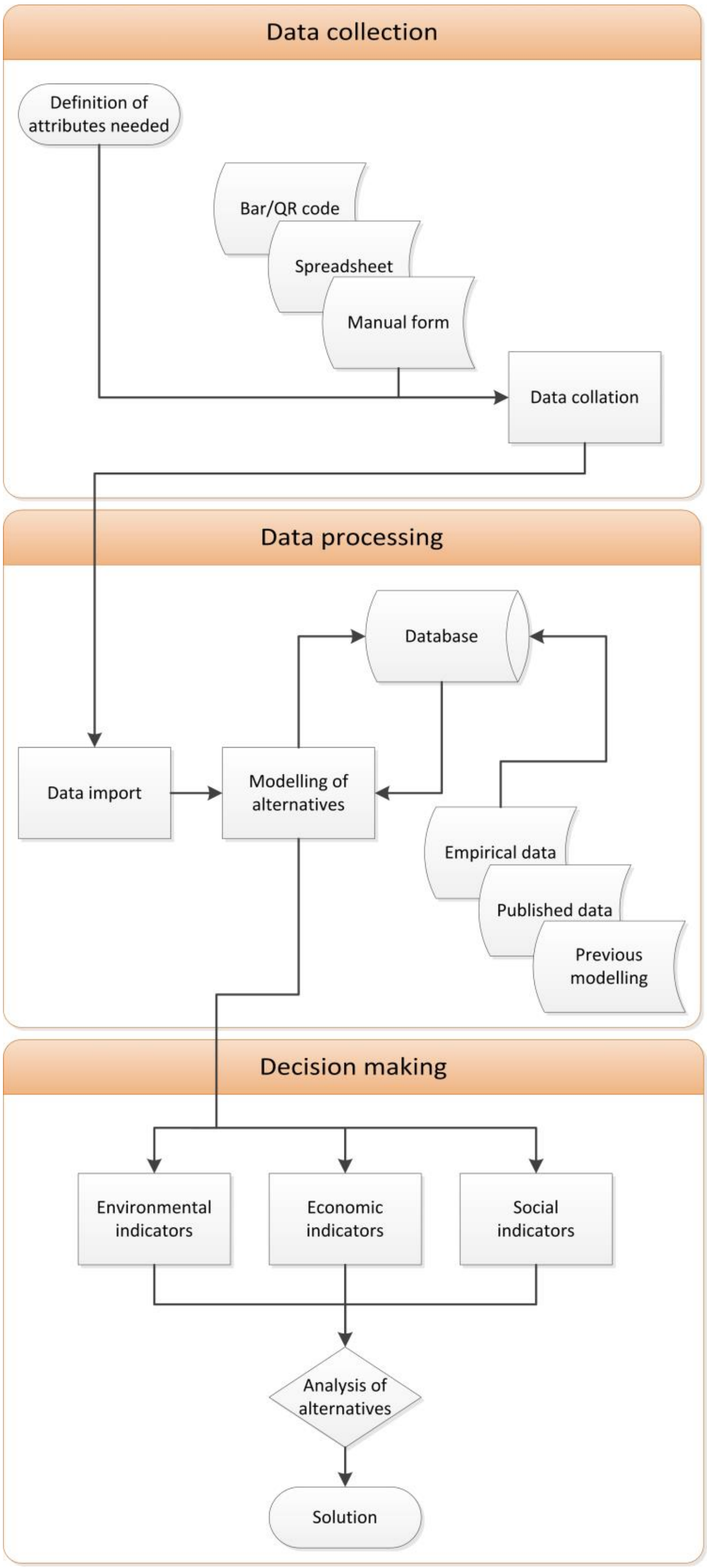


Figure 8-2. Major phases in the operation of the FWMMP

1. The first phase is the selection of the relevant attributes from each of the four stages in Figure 8-1. The attributes selected are likely to vary for each FW type or food

company. For instance, in order to manage a fruit juice waste the pH value may be needed, as opposed to cereal waste, where the carbohydrate content is more pertinent. Data can be collected manually, using spreadsheets, or, principally when assessing the final food product, scanning a barcode or QR code.

2. Secondly, data must be processed using the FWMMP, or, if a software tool is available, data must be introduced into the system. After that, relationships must be built between the attributes identified (which is explained in Chapter 9). As a result, a mathematical model that enables the estimation of the value of one attribute through the values of other known attributes can be developed. For instance, the nutrient composition of compost can be estimated knowing the characteristics of the FW to treat and the composting process used. Additional data is necessary for the attributes that cannot be estimated through calculations from other attributes. For instance, the pH value of FW cannot be calculated from other attributes and therefore must be obtained from empirical data (e.g. using analytical methods in a laboratory), published research and databases, or using models developed previously. In this way, collected data and additional data needed are processed, modelling FWMSs as a result.
3. Finally, the modelling process allows obtaining the values of the sustainability indicators defined in phase 1. These are compared for each FWMS using a pre-established criterion. The assessment of these indicators helps to select a tailored FWM practice that optimises the outputs generated.

Alternatively, the procedure can also be applied following the reverse order than that of Figure 8-1. In this way, firstly the relevant sustainability indicators to the company under consideration must be identified, and then the FWM performance factors required to calculate the sustainability indicators can be assessed, continuing the process until the FW parameters needed are found. For instance, a food company may decide to base its FWM decision on a reduction of greenhouse gases emissions exclusively, and consider only animal feeding and anaerobic digestion as potential FWMSs. In this case, the sustainability indicators can be reduced to the emission of CO_2, CH_4, and N_2O. Performance factors needed to calculate these indicators would be biogas production rate and methane content of biogas. Management variables would include variables needed to model the anaerobic digestion process and distance to transport FW. Finally, the FW parameters needed would be those referring to animal feeding and anaerobic digestion only. In these cases, the FWMMP can be simplified removing unneeded attributes from the procedure.

The key attributes required to implement the FWMMP are classified and explained in Section 8.3.

8.3 Stages of the Food Waste Management Modelling Procedure

This section defines the data needed to model FWM. Each stage of the process is presented, and the most relevant parameters, variables, factors and indicators are identified and arranged in Tables 8-1 to 8-10.

The list of attributes was compiled after undertaking an extensive study of the five FWMSs considered, which are, as justified in Section 7.5.1.1, redistribution for human consumption, animal feeding, anaerobic digestion, composting and thermal treatment with energy recovery. The attributes needed to model the processes and characterise raw materials and outputs generated were identified and classified according to the FWMMP. Redundant attributes were removed or combined into a single attribute. Each attribute was assessed independently and their inclusion in the list was decided upon its relevance to support the aim of the FWMMP. Therefore, some attributes were discarded if they were found only in a very small number of publications (e.g. lowest pH achieved during composting) or were not relevant to FWM (e.g. N_2 content in biogas). The lists are intended to be not only exhaustive but also determinative and practical. It includes the attributes needed to model FWM to a great level of detail, based on a thorough analysis of the five FWMS considered. Nevertheless, the user of the FWMMP can add or remove attributes in the lists in order to adapt it to their specific needs.

The tables are comprised of four columns: first column shows the attribute considered, second column gives an example of that type of attribute or a unit commonly used to measure it, third column presents the FWMSs that need the attribute to be defined ('R': redistribution for human consumption, 'AF': animal feeding, 'AD': anaerobic digestion, 'C': composting and 'TT': thermal treatment with energy recovery; in some tables 'T' has been added to represent transportation, which affects the five FWMSs), and the last column gives one example of published research where the attribute is used per type of FWMS listed in the third column. Consequently, the references from the fourth column, which include published research and legislation, confirm the need to consider the attribute for the FWMS assessed.

8.3.1 Parameters to define characteristics of FW

FWs are very diverse in their characteristics and composition. Parameters to estimate characteristics of FWs are classified into two categories: qualitative and quantitative parameters. Quantitative parameters are further subdivided into two sub-categories: primary and secondary parameters. These parameters are defined below and listed in Tables 8-1 to 8-3.

8.3.1.1 Qualitative parameters

Qualitative parameters have been identified and described in Section 7.4. They do not have a numerical value and are used to describe the qualitative characteristics of the FW. They provide an initial recommendation on the most sustainable FWMS available. Qualitative FW parameters are listed in Table 8-1 below.

8.3.1.2 Quantitative parameters

Quantitative parameters provide more specific and quantitative information about the characteristics of the FW. Quantitative parameters are needed to estimate quantitative results from FWM. They are further subdivided into primary and secondary.

Table 8-1. Qualitative FW parameters

Parameter	Example or unit	FWMS	Reference
Edibility	Edible / Inedible	R, AF	Section 7.4 of this thesis
State	Eatable / Not eatable / Uneatable for humans, eatable for animals	R, AF	
Origin	Animal based / Plant based	AF, AD, C	
Complexity	Single / Mixed	AF, AD, C	
Animal-material presence	Meat / Animal product / By-product from animal bodies / In contact with ABP / Not in contact with ABP	AF, AD, C	
Treatment	Processed / Unprocessed	R	
Packaging	Packaged / Unpackaged/separable from packaging	AF, AD, C	
Packaging biodegradability	Biodegradable package / Non-biodegradable package	AD, C	
Stage of the supply chain	Catering waste / Non-catering waste	AF	

Primary parameters are those parameters which cannot be determined by other parameters. In order to obtain the value for primary parameters, experimental analysis, review of published literature or data collection from databases must be carried out. The values of primary parameters are specific and different for the type and quantity of FW under consideration, e.g. chemical composition. Quantitative primary FW parameters are listed in Table 8-2 below.

Table 8-2. Quantitative primary FW parameters

Parameter	Example or unit	FWMS	Reference
Production or flow rate	kg or m^3 / day	R, AF, AD, C, TT	R: The Commission of the European Communities (2005), AF: European Commission 2005b), AD: British Standards Institution (2014), C: British Standards Institution (2011), TT: Brunner & Rechberger (2014)
Carbohydrate content and composition	% mass	AF, AD, C, TT	AF: Parfitt, Stanley, et al. (2016), AD: Batstone et al. (2002), C: Chang & Hsu (2008), TT: Caton et al. (2010)
Fat content and composition	% mass	AF, AD, C, TT	AF: San Martin et al. (2015), AD: Batstone et al. (2002), C: Chang & Hsu (2008), TT: Caton et al. (2010)
Protein content and composition	% mass	AF, AD, C, TT	
Vitamin content and composition	% mass	AD, C, TT	AD: Climenhaga (2008), C: Ipek et al. (2005), TT: Caton et al. (2010)
Other organic compounds	% mass	R, AF, AD, C, TT	R: The Commission of the European Communities (2006), AF: European Commission (2002), AD: British Standards Institution (2014), C: British Standards Institution (2011), TT: Caton et al. (2010)
Inorganic content and composition	% mass	R, AF, AD, C, TT	R: WHO/FAO (1995), AF: European Commission (2002), AD: Fisgativa et al. (2015), C: Himanen & Hänninen (2009), TT: Caton et al. (2010)
Moisture content	% mass	AD, C, TT	AD: Zhang et al. (2007), C: Chang & Hsu (2008), TT: Caton et al. (2010)
Biological hazard	CFU/g fresh matter	R, AF, AD, C, TT	R: The Commission of the European Communities (2005), AF: European Commission (2005b), AD: British Standards Institution (2014), C: British Standards Institution (2011), TT: Brunner & Rechberger (2014)
pH	0-14	AD, C	AD: Fisgativa et al. (2015), C: Chang & Chen (2010)
Particle size	mm	AD, C	AD: Zhang et al. (2015), C: Nakasaki et al. (2015)

It is highly beneficial to provide a detailed analysis of the composition of the FW: the main components of the FW should be identified (e.g. percentage of carbohydrates in the FW) and subdivided into its minor constituents (for carbohydrates: the exact content of glucose, lactose, amylose and other relevant substances).

'Other organic compounds' refer to those not included explicitly in the other attributes of the list, and include mainly pollutants or non-nutritive organic substances such as pesticides, fertilisers and dioxins. 'Inorganic compounds' are those that are present in form of salt or ion, e.g. NaCl, Na^+, K^+, Cl^- and F^-.

'Biological hazard' refer to the presence of microbiological activity that affect the quality of the FW, such as bacteria, yeasts and moulds. The presence or absence of biological hazard would have already been elucidated during the assessment of the qualitative FW parameter 'state', but here the type of microorganism must be identified and quantified.

Secondary parameters are parameters that can be calculated using values of primary parameters. In order to do so, mathematical relations must be built between secondary and primary parameters. Additionally, secondary parameters can also be obtained from experimental analysis, published literature or databases. Secondary parameters can be defined when assessing FWMSs, e.g. total Kjeldahl nitrogen (which depends on protein, vitamin and other organic content and composition) is only relevant to evaluate anaerobic digestion and composting. Quantitative secondary FW parameters are listed in Table 8-3.

'Hazardous materials' include those substances containing a biological hazard, pollutants and any other material which can cause a harmful effect to people, the environment or the FWMS (e.g. stones and sharp objects).

'Energy value' must not be confused with 'calorific value': the former refers to the energy obtained from the digestion of the FW (which is relevant for animal feeding) and the latter to the energy obtained through a thermal treatment of the waste (i.e. incineration, pyrolysis or gasification).

Three different ratios of chemical elements have been added to the table, since different elements are relevant for different FWMSs: C:H:O:N:P:S ratio for anaerobic digestion, C:N ratio for composting and C:H:O:N:S:Cl ratio for thermal treatment with energy recovery. For each FWMS, the source that provides a more itemised ratio of chemical elements was selected. For instance, although for AD a number of sources consider C:N ratio only, a ratio of C:H:O:N:P:S was selected as suggested by Hidalgo et al. (2016).

Table 8-3. Quantitative secondary FW parameters

Parameter	Example or unit	FWMS	Reference
Density	kg/m^3	R, AF, AD, C, TT	R: Bilska et al. (2016), AF: European Commission (2002), AD: Fisgativa et al. (2015), C: WRAP (n.d.), TT: Lee et al. (2007)
Hazardous materials	Type and % mass	R, AF, AD, C, TT	
Energy value	kcal/kg	AF	Parfitt, Stanley, et al. (2016)
Volatile solids (VS)	% mass of TS	AD, C, TT	AD: Zhang et al. (2007), C: Chang et al. (2006), TT: Ahmed & Gupta (2010)
Total solids (TS)	% mass	AD, C, TT	AD: Kumar et al. (2015), C: Wang & Ai (2016), TT: Ahmed & Gupta (2010)
Total Kjeldahl nitrogen (TKN)	mg/g TS	AD, C	AD: Kumar et al. (2015), C: Adhikari et al. (2008)
Total ammonia nitrogen (TAN)	mg/l	AD	Fisgativa et al. (2015)
Chemical oxygen demand (COD)	mg/l	AD	
C:H:O:N:P:S ratio	C:H:O:N:P:S mass	AD	Hidalgo et al. (2016)
C:H:O:N:S:Cl ratio	C:H:O:N:S:Cl mass	TT	Caton et al. (2010)
C:N ratio	C:N mass	C	Chang & Chen (2010)
Ash	% mass	C, TT	C: Chang & Chen (2010), TT: Caton et al. (2010)
Porosity	% volume	C	Cooperband (2002)
Calorific value	MJ/kg	TT	Bujak & Sitarz (2016)

Volatile fatty acids (VFA) content is of relevance to the anaerobic digestion process, since it inhibits the digestion (Kondusamy & Kalamdhad 2014). However it was not included in this list since volatile fatty acids are generated during the process and are present in the raw material in low quantities. Initial VFA is included in 'fat content and composition' quantitative primary FW parameter.

Some of the FW parameters introduced in this section are also needed to assess the performance of the processes, e.g. the final moisture content of compost gives information about the yield of the composting process. In addition, the value of some parameters can be corrected during the treatment (e.g. addition of a buffer to control pH in the anaerobic digester) and therefore can also be considered FWM process variables. These types of parameters should be monitored during the process and also evaluated at the end of the treatment as performance factors.

8.3.2 Variables to model FWM processes and company status

In addition to parameters based on FW characteristics, there are a number of variables which depends on other factors. They can be classified into two major categories: FWM process variables and company status variables, which are defined below and listed in Table 8-4.

FWM process variables need to be defined in order to estimate the performance of the different FWMSs, e.g. the air ratio in a composting process is a key variable in order to estimate the final composition of the compost obtained. The variables must be different and specific for each FWMS considered. The values of these variables must be determined for each type of FW treated, since optimum values are different for each feedstock (e.g. solid and liquid FW). Depending on the precision of the modelling needed, assessing each FW batch can also be necessary, since FW compositions may change from batch to batch (e.g. different levels of ripeness for the same type of FW would cause variations in chemical compositions of the FW).

Some of the FWM process variables are also relevant to evaluate the performance of the processes, e.g. nutrient content in the digestate material obtained from anaerobic digestion. This type of parameter should be monitored during the process and also evaluated at the end of the treatment as performance factor.

Transportation ('T') has been added to the list in the column of FWMS, since it should be analysed for all FWMSs.

Company status variables do not change from batch to batch as they are constant for a certain company. 'Company' refers to the food manufacturer that generates the FW or the waste management processor, which in some cases may be the same. For instance, the type and volume of equipment available to treat FW in the company and the distance to waste processors that take charge of the FW generally remain unchanged. Clearly, these variables may change over longer periods, e.g. new equipment can be purchased, but these variables would be considered fixed variables as the time to implement the changes is longer than the time given to manage FW. When the variables (or their values) change, they will have to be amended in the model.

Table 8-4. FWM process and company status variables

Variable	Example or unit	FWMS	Reference
Distance to transport FW	km	T	den Boer et al. (2009)
Type of equipment available	E.g. Upflow anaerobic sludge blanket reactor (UASB)	AD, C, TT	AD: Mao et al. (2015), C: Cooperband (2002), TT: Defra (2013b)
Volume of equipment available	m^3	AD, C, TT	
Number of stages	Number and type	AD, C, TT	AD: Mao et al. (2015), C: Chang et al. (2006), TT: Lohri et al. (2015)
Temperature	°C	AD, C, TT	AD: Mao et al. (2015), C: Cooperband (2002), TT: Caton et al. (2010)
Process time	Days / hours	AD, C, TT	
Treatment method	Batch / Continuous / Semi-continuous	AD, C, TT	AD: Mao et al. (2015), C: Kwon & Lee (2004), Suler & Finstein (1977), TT: Lohri et al. (2015)
Pre-treatment	Yes (type) / No	AD, C, TT	AD: Zhang et al. (2014), C: Nakasaki et al. (2015), TT: Lohri et al. (2015)
Additives / Catalysts	Yes (type and concentration) / No	AD, C, TT	AD: Mao et al. (2015), C: Peigne & Girardin (2004), TT: Ahmed & Gupta (2010)
Co-products	Type and quantity of co-product	AD, C, TT	AD: Mao et al. (2015), C: Cooperband (2002), TT: Manfredi & Cristobal (2016)
Inoculum / Seeding	Type and % mass	AD, C	AD: Kondusamy & Kalamdhad (2014), C: Chang et al. (2006)
Agitation / Stirring	Yes (type and speed / periodicity) / No	AD, C	AD: Leung & Wang (2016), C: Cooperband (2002)
pH	0-14	AD, C	AD: Mao et al. (2015), C: Cooperband (2002)
Organic loading rate (OLR)	kg VS/m^3 day	AD	Mao et al. (2015)
Hydraulic retention time (HRT)	Days	AD	
Composting of digestate	Yes (type) / No	AD	Kondusamy & Kalamdhad (2014)
Oxygen concentration / Air ratio	%	C, TT	C: Cooperband (2002), TT: Caton et al. (2010)
Pile size	cm high, m wide	C	Cooperband (2002)
Pressure	Bar	TT	Lohri et al. (2015)
Steam injection	Yes (quantity, temperature, pressure) / No	TT	Ramzan et al. (2011)

'Distance to transport FW' is the crucial variable to assess economic costs and environmental impacts of transportation of FW (which is relevant to all FWMSs but especially for redistribution and animal feeding). There are other variables in FW transportation, such as the weight and volume capacity of trucks, route topography, driving style and traffic, but these have been considered less relevant and have been excluded.

'Number of stages' refers to processes that comprise more than one sub-process, e.g. two-stage anaerobic digestion. Variables must be defined for all stages, e.g. temperature and pressure at each stage.

For anaerobic digestion, 'hydraulic retention time (HRT)' has been considered besides 'process time'. 'HRT' is the time FW is retained in the digester, whilst 'process time' refers to the total time to treat the FW in the facilities until final results are achieved, which can include biogas upgrading, digestate concentration and other processes before and after the digestion process. 'HRT' is needed to model the anaerobic digestion process only whilst 'process time' is useful to assess the efficiency of the entire FWM process.

It is important to notice that 'pH' as a FWM process variable refers to the pH determined to be used for the treatment of FW (i.e. pH in the digester or composting vessel/facility), as opposed to 'pH' as a quantitative primary FW parameter, which is the initial pH of FW before treatment.

The FWMMP is useful to analyse current FWMSs which are possible for the company. If new FWMSs are to be considered and they require an economic investment (e.g. purchasing new equipment), the 'availability of economic investment' can be considered a company status variable useful to analyse the feasibility of such proposed FWM modification.

Several variables can be considered to belong to FWM process variables and company status variables as they depend on both categories, e.g. addition of co-products to the FW to be treated depend on the availability of co-products for the company, thus it is a company status variable, but is also a variable needed to model FWM processes (anaerobic digestion, composting and thermal treatment with energy recovery), so it can also be considered a FWM process variable. Consequently, FWM process variables and company status variables have been combined and are not distinguished in Table 8-4.

8.3.3 Factors to assess the performance of FWM practices

Once the data needed to characterise FW, FWM processes and company status have been collected, the performance of the different FWMSs can be estimated through modelling of the different processes. This can be done manually by the user or using a software tool to automate the procedure. In the second case, the user introduces the collected data into the tool and this would generate values for the FWM performance factors. The list of performance factors can be found in Table 8-5.

For this purpose, firstly a set of factors to assess the performance of FWM practices must be defined for each FWMS considered. For instance, for redistribution for human consumption the most relevant factor is usually 'quantity of food redistributed'. Secondly, these factors must be connected to the parameters and variables identified in Sections 8.3.1 and 8.3.2 using mathematical relationships. As a result, the value of these factors could be calculated using parameters and variables that have been previously assessed.

The terms 'digestate composition' and 'compost composition' are generic, and they refer to the need to obtain the specific composition of both materials. The preciseness of those compositions (i.e. the number of components analysed, e.g. concentration of different aminoacids) depend on the degree of precision required for the company and the type of sustainability indicators to be determined (Section 8.3.4). For instance, if the only nutrient to be assessed as environmental impact to soil is nitrogen, only protein and vitamin content are necessary, and carbohydrate and fat content can be discarded from the analysis, as they do not contain nitrogen. In general, it can be assumed that a detailed composition of the different materials obtained is beneficial as a more representative estimation of the outputs generated can be obtained.

Table 8-5. FWM performance factors

Factor	Example or unit	FWMS	Reference
Quantity of food redistributed	kg/day	R	Bilska et al. (2016)
Quantity animal feed produced	kg/day	AF	Westendorf (2000)
Biogas production rate	l/day	AD	Chen et al. (2010)
[CH4] in biogas	% volume	AD	
Digestate flow rate	l/day	AD	
Digestate composition	% mass	AD	
Compost production rate	kg/day	C	Cooperband (2002)
Compost composition	% mass	C	
Gas flow rate	Nm3/day	TT	Buragohain et al. (2012)
Lower heating value of gas	MJ/m3	TT	
Char production rate	kg/day	TT	Lohri et al. (2015)
Heating value of char	MJ/kg	TT	

On the other hand, for biogas composition the methane content has been the only factor included in Table 8-5. Similarly, a more precise analysis of other gases of the biogas allows a representative estimation of the ramifications of FWM, such as leaks of H_2S to the atmosphere. The same applies to the compositions of the gas and char obtained from thermal treatments. In this list only the most relevant and used factors to assess the performance of the FWMSs studied are included.

8.3.4 Sustainability indicators to evaluate ramifications of FWMSs

Since FWM performance factors are valued using different units, they must be converted into comparable indicators in order to contrast the results obtained from different FWMSs. Considering the aim of this research to increase the sustainability of FWM, the indicators chosen are associated to the three pillars of sustainability: environmental, economic and social ramifications.

Mathematical models are needed to link the sustainability indicators with the FWM performance factors. However, occasionally the sustainability indicator cannot be calculated from performance factors (e.g. noise), and in these situations the sustainability indicator must be obtained through direct measurements or using FW parameters and FWM process and company status variables.

In order to use the FWMMP, only environmental, economic and social ramifications associated with FWM must be considered. Impacts of the food during its life cycle (e.g. harvesting, storage and manufacturing) are not included in the FWMMP since they do not affect FWM decisions, i.e. the ramifications have already occurred before the food was wasted. Consequently, a product life-cycle approach was not appropriate to assess different possible solutions and only end-of-life impacts were studied. End-of-life impacts include ramifications generated from the moment FW is generated until the management of FW is completed (i.e. a life-cycle approach of the waste, and not the product, was considered).

Transportation ('T') is included in the FWMMP, and this should be analysed for all FWMSs, as potentially all management options include a transportation of FW.

8.3.4.1 Environmental indicators

Environmental indicators assess the impact on the environment and/or human health of the different FWMSs. These impacts are generally negative (e.g. toxic gases emitted), but can be positive in certain occasions (e.g. use of waste for the removal of pollutants in wastewater).

In order to better understand the environmental impact generated managing FW, it can be useful to classify the indicators into the different types of impacts created, for instance greenhouse gas emissions (e.g. CO_2, CH_4, N_2O), eco-toxicity (e.g. NMVOC, NH_3, H_2S), acidification (e.g. SO_2, NOx, NH_3) and photochemical oxidation (e.g. VOC, NOx, CH_4). This could be considered in future versions of the FWMMP, however for the current purpose of the FWMMP only quantities of substances emitted are accounted.

The list of environmental impacts have been divided into three tables, Tables 8-6 to 8-8, to describe impacts to air, water and soil respectively. Some indicators can be present in more than one table, e.g. particles that are emitted to the atmosphere can precipitate and pollute water and soil. It must also be noted that some indicators include the assessment of other indicators, e.g. 'TOC' includes 'NMVOCs', and 'leaching value' includes presence of chemical elements such as 'Sb', 'Cd' and 'Cr'. These types of 'general indicators' were included in Tables 8-6 to 8-8 when they are commonly used to assess environmental impacts of a FWMS.

Table 8-6 lists the environmental indicators used to assess impacts of FWM to air.

All five FWMSs studied generate a range of emissions to the atmosphere. For redistribution for human consumption and animal feeding, these emissions are generated due to transportation, since these options potentially do not require any treatment to process the FW. In order to decide which emissions to include in Table 8-6, a study was carried out to identify the substances which can negatively impact the environment and/or human health. For this purpose, the following documentation was reviewed and used to complete a list of damaging atmospheric emissions: Parliament of the United Kingdom (2008), The European Parliament and the Council of the European Union (2010), The Secretary of State (2010a), European Commission (2013) and European Environment Agency (2015). Subsequently, when reviewing published research on emissions from the five FWMSs, the emissions found were compared against the list created with the aforementioned regulation. Providing the substance emitted by the FWMS was in this list, it was added to Table 8-6, proving that the substance creates a negative environmental impact.

Table 8-6. Environmental indicators: impacts to air

Indicator	Example or unit	FWMS	Reference
Total emissions to air	m^3/day	T, AD, C, TT	T: den Boer et al. (2009), AD: Whiting & Azapagic (2014), C: Khoo et al. (2010), TT: European Commission (2006c)
CO_2	mg/m^3	T, AD, C, TT	
CH_4	mg/m^3	T, AD, C, TT	T: den Boer et al. (2009), AD: Whiting & Azapagic (2014), C: Börjesson & Berglund (2007), TT: European Commission (2006c)
N_2O	mg/m^3	T, AD, C, TT	T: den Boer et al. (2009), AD: Møller et al. (2009), C: Amlinger et al. (2008), TT: European Commission (2006c)
NOx	mg/m^3	T, AD, C, TT	T: den Boer et al. (2009), AD: Styles et al. (2016), C: Peigne & Girardin (2004), TT: European Commission (2006c)
Non-methane volatile organic compounds (NMVOC)	mg/m^3	T, AD, C, TT	T: Environmental Protection UK (n.d.), AD: Gerardi (2003), C: Amlinger et al. (2008), TT: European Commission (2006c)
Total organic carbon (TOC)	mg/m^3	T, TT	T: Wada et al. (2015), TT: European Commission (2006c)
NH_3	mg/m^3	AD, C, TT	AD: Whiting & Azapagic (2014), C: Khoo et al. (2010), TT: European Commission (2006c)
SOx	mg/m^3	AD, C, TT	AD: Beylot et al. (2015), C: Zhao & Deng (2014), TT: European Commission (2006c)
HCl	mg/m^3	AD, C, TT	AD: Zhao & Deng (2014), C: Zhao & Deng (2014), TT: European Commission (2006c)
Dioxins, furans, PAH, PCBs and products alike	mg/m^3	AD, C, TT	AD: Haight (2005), C: Haight (2005), TT: European Commission (2006c)
H_2S	mg/m^3	AD, C	AD: Gerardi (2003), C: Peigne & Girardin (2004)
CO	mg/m^3	AD, C, TT	AD: Gerardi (2003), C: Zhao & Deng (2014), TT: European Commission (2006c)
Dust	mg/m^3	T, TT	T: Wada et al. (2015), TT: European Commission (2006a)
PM<10	mg/m^3	T, AD, C, TT	T: den Boer et al. (2009), AD: Cherubini et al. (2009), C: Zhao & Deng (2014), TT: European Commission (2006c)
PM<2.5	mg/m^3	T, TT	T: den Boer et al. (2009), TT: European Commission (2006c)
As	mg/m^3	TT	Lee et al. (2007)
Cd	mg/m^3	TT	
Hg	mg/m^3	TT	
Zn	mg/m^3	TT	
Cr	mg/m^3	TT	
Ni	mg/m^3	TT	
Pb	mg/m^3	TT	
Cu	mg/m^3	TT	

The indicators included in the list refer to emissions of the main process and also of additional processes if they are of relevance. For instance, for anaerobic digestion most of CO_2 emitted is generated during biogas combustion, and most CH_4 and NH_3 emitted is related to open storage of digestate and its application to the land (Whiting & Azapagic 2014). These additional processes can be removed from the analysis if they do not take place in the company under consideration (e.g. the biogas is combusted in a different facility).

One of the main sources used to study emissions from thermal treatments with energy recovery was the Reference Document on the Best Available Techniques for Waste Incineration (European Commission 2006c), which is not specific to FW. When analysing types of substances that can be emitted from incineration, the substances were assessed and included in Table 8-6 only if they can be present in food products or food packaging. For this reason, substances such as hydrogen fluoride (HF) were not included in Table 8-6, since its main source are fluorinated plastic, fluorinated textiles and decomposition of CaF_2 during the incineration of sludge.

Table 8-7 below lists the environmental indicators used to assess impacts of FWM to water.

K, Ca, Mg and S were found as potential impacts to soil for anaerobic digestion and soil and water for composting. Since the application of digestate from anaerobic digestion to land is similar to that of composting, and these substances were found as potential impacts to water from composting, they were also considered for anaerobic digestion in Table 8-7.

Table 8-8 lists the environmental indicators used to assess impacts of FWM to soil.

Table 8-7. Environmental indicators: impacts to water

Indicator	Example or unit	FWMS	Reference
Wastewater flow	m^3/day	AF, AD, C, TT	AF: Lee et al. (2007), AD: Deepanraj et al. (2015), C: Peigne & Girardin (2004), TT: European Commission (2006c)
Chemical oxygen demand (COD)	g/m^3	AF, AD, C, TT	
Biochemical oxygen demand (BOD)	g/m^3	AF, AD, C, TT	AF: Lee et al. (2007), AD: Suwannarat & Ritchie (2015), C: Peigne & Girardin (2004), TT: Abbasi & Abbasi (2010)
Total suspended solids (TSS)	g/m^3	AF, AD, C, TT	AF: Lee et al. (2007), AD: Wu et al. (2016), C: Lasaridi & Stentiford (1998), TT: Abbasi & Abbasi (2010)
...			

		…	
NH_4^+	g/m^3	AF, C	AF: Lee et al. (2007), C: Peigne & Girardin (2004)
P	g P_2O_5/PO_4^{-3} / m^3	AF, AD, C	AF: Lee et al. (2007), AD: Vögeli et al. (2014), C: British Standards Institution (2011)
Cd	g/m^3	AD, C, TT	AD: Xu et al. (2015), C: British Standards Institution (2011), TT: European Commission (2006c)
Zn	g/m^3	AD, C, TT	
Cr	g/m^3	AD, C, TT	
Pb	g/m^3	AD, C, TT	
NO_3^-	g/m^3	AD, C	AD: Ortner et al. (2013), C: Peigne & Girardin (2004)
K	g/m^3	AD, C	AD: Levén et al. (2012), C: British Standards Institution (2011)
Ca	g/m^3	AD, C	AD: Brändli, Bucheli, et al. (2007), C: British Standards Institution (2011)
Mg	g/m^3	AD, C	AD: Levén et al. (2012), C: British Standards Institution (2011)
S	g/m^3	AD, C	AD: Opatokun et al. (2015), C: British Standards Institution (2011)
Hg	g/m^3	AD, TT	AD: Xu et al. (2015), TT: European Commission (2006c)
Cu	g/m^3	AD, TT	
Ni	g/m^3	AD, TT	
As	g/m^3	AD, TT	
V	g/m^3	AD	Xu et al. (2015)
Be	g/m^3	AD	
Br	g/m^3	AD	
Se	g/m^3	AD	
Co	g/m^3	AD	
F^-	g/m^3	C, TT	C: British Standards Institution (2011), TT: European Commission (2006c)
B	g/m^3	C	British Standards Institution (2011)
Fe	g/m^3	C	
Mn	g/m^3	C	
Na	g/m^3	C	
Total organic carbon (TOC)	g/m^3	TT	European Commission (2006c)
Dioxins, furans and PCBs	mg/m^3	TT	
SO_4^{-2}	g/m^3	TT	
Cl^-	g/m^3	TT	

Table 8-8. Environmental indicators: impacts to soil

Indicator	Example or unit	FWMS	Reference
Solid residue flow rate	kg/day	AD, C, TT	AD: British Standards Institution (2014), C: British Standards Institution (2011), TT: European Commission (2006c)
Cu	mg/kg	AD, C, TT	
Zn	mg/kg	AD, C, TT	
Nutrient content: N	g N/kg	AD, C	AD: Levén et al. (2012), C: WRAP (2016)
Nutrient content: P	g P_2O_5/kg	AD, C	
Nutrient content: K	g K_2O/kg	AD, C	
Nutrient content: Mg	g MgO/kg	AD, C	
Nutrient content: S	g SO_3/kg	AD, C	AD: Opatokun et al. (2015), C: WRAP (2016)
Nutrient content: Ca	g $CaCO_3$/kg	AD, C	AD: Brändli, Bucheli, et al. (2007), C: Brändli, Bucheli, et al. (2007)
Moisture content	g/kg	AD, C	AD: British Standards Institution (2014), C: British Standards Institution (2011)
Loss on ignition / VS / TOC	g/kg	AD, C, TT	AD: British Standards Institution (2014), C: British Standards Institution (2011), TT: European Commission (2006c)
pH / neutralising value	0-14	AD, C	AD: British Standards Institution (2014), C: British Standards Institution (2011)
Dioxins, furans, PAH, PCBs and products alike	ng I-TEQ/kg dry	AD, C, TT	AD: Brändli, Bucheli, et al. (2007), C: Brändli, Bucheli, et al. (2007), TT: European Commission (2006c)
Fungicides, herbicides, insecticides, acaricides	mg/t dry	AD, C	AD: Brändli, Bucheli, et al. (2007), C: Brändli, Bucheli, et al. (2007)
E. coli	CFU/g fresh matter	AD, C	AD: British Standards Institution (2014), C: British Standards Institution (2011)
Salmonella spp	CFU/g fresh matter	AD, C	
Cd	mg/kg	AD, C	
Cr	mg/kg	AD, C	
Pb	mg/kg	AD, C	
Hg	mg/kg	AD, C	
Ni	mg/kg	AD, C	
VFAs	COD/g VS	AD, C	
		…	

		...	
Total glass, metal, plastic and any 'other' non-stone, man-made fragments > 2 mm	% m/m dry matter, no sharps	AD, C	
Stones > 5 mm	% m/m dry matter	AD, C	AD: British Standards Institution (2014), C: British Standards Institution (2011)
Total physical contaminants (excluding stones)	kg/t	AD	British Standards Institution (2014)
Nutrient content: Na	mg WS Cl/kg	C	British Standards Institution (2011)
Nutrient content: B	mg/kg	C	
Nutrient content: Fe	mg/kg	C	
Nutrient content: Mn	mg/kg	C	
Particle size distribution	mm	C	
C:N	C:N (mass)	C	
Electrical conductivity	mS/cm	C	
Microbial respiration rate	mg CO_2/g organic matter per day	C	
Germination seeds or propagule regrowth	mean number/litre of compost	C	
Stones > 4 mm in grades other than "mulch"	% mass	C	
Stones > 4 mm in "mulch" grade	% mass	C	
Leaching value	mg/kg	TT	European Commission (2006c)
Sb	mg/kg	TT	
Mo	mg/kg	TT	
Cl-	mg/kg	TT	
SO_4^{-2}	mg/kg	TT	

Some of the pollutants found after managing FW are related to secondary activities linked to the FWM, such as PAH (polyaromatic hydrocarbons) deposited to the soil from fossil fuel combustion and traffic near the waste management facility.

8.3.4.2 Economic indicators

Economic indicators are used to assess the economic result from FWM, which can be either positive (economic benefit obtained from management of the FW) or negative (economic cost to treat or dispose of the waste). FWMSs with significantly less favourable economic implications than currently-followed alternatives can be discarded at this stage. The list of economic indicators used in the FWMMP can be found in the Table 8-9.

'Management cost' includes the direct economic costs of FWM (e.g. economic cost of the water added to the anaerobic digester) and also indirect economic costs. Indirect costs include aspects such as storage and transportation costs, which are more relevant for redistribution for human consumption and animal feeding since their direct costs should be nearly zero (because on most occasions there is not any processing required). In the FWMMP, redistribution generally does not provide any direct economic income to the company because the product is not sold, however the storage costs are generally lower than for the other FWMSs, since the food must be redistributed rapidly before it expires. Nevertheless, costs of redistribution per day (for storage costs) and per mile (for transportation costs) are generally higher than for any other FWMS, since the cold chain may be required at all times for redistribution for human consumption.

Solid material from the indicator 'economic value of solid material' refers to animal feed, digestate from anaerobic digestion (although digestate can be solid or liquid), compost, and

Table 8-9. Economic indicators

Indicator	Example or unit	FWMS	Reference
Management cost	£	R, AF, AD, C, TT	R: Giuseppe et al. (2014), AF: Kim et al. (2010), AD: Gebrezgabher et al. (2010), C: Ruggieri et al. (2009), TT : Herva & Roca (2013)
Economic value of solid material	£/t	AF, AD, C, TT	AF: Parfitt, Stanley, et al. (2016), AD: Styles et al. (2016), C: Rothenberger et al. (2006), TT: Bujak (2015)
Heat recovered / Output power	kJ/min	AD, TT	AD: Styles et al. (2016), TT: Ahmed & Gupta (2010)
Biogas rate	Nm^3/day	AD	Styles et al. (2016)
[CH_4] in biogas	%	AD	

char from thermal treatment with energy recovery. These materials can be usually sold and an economic income can be obtained from them.

In the case of anaerobic digestion, the main economic income is generated from the biogas obtained, which can be sold or used in-situ to produce energy. Therefore, the economic income obtained is dependent on the biogas production rate and concentration of methane in the biogas. It is worth noting that these two economic indicators are also used as performance indicators.

In the case of thermal treatment with energy recovery, the main economic income is generated from the amount of heat recovered. If the heat is used in situ to obtain electrical energy, the economic indicator for this FWMS would be the output power produced.

8.3.4.3 Social indicators

Social indicators incorporate social considerations not addressed with environmental and economic indicators. They can be either positive (e.g. food redistributed to people in need) or negative (e.g. loss of jobs). The list of social indicators used in the FWMMP can be found in the Table 8-10 below.

Table 8-10. Social indicators

Indicator	Example or unit	FWMS	Reference
Support of local economies	Yes (number of people benefitted / tonne) / No	R, AF, AD, C, TT	R: Buksti et al. (2015), AF: Sugiura et al. (2009), AD: Chong et al. (2016), C: Chong et al. (2016), TT: Chong et al. (2016)
Job creation	Yes (number of people benefitted / tonne) / No	R, AF, AD, C, TT	R: Buksti et al. (2015), AF: Defra et al. (2016), AD: Vögeli et al. (2014), C: Rothenberger et al. (2006), TT: Friends of the Earth (2010)
Noise	dB	T, AD, C, TT	T: den Boer et al. (2009), AD: Kythreotou et al. (2014), C: Cooperband (2002), TT: European Commission (2006c)
NIMBY syndrome	Yes (number of people affected/tonne) / No	AD, C, TT	AD: Chong et al. (2016), C: Chong et al. (2016), TT: Chong et al. (2016)
Feeding people	Yes (number of people benefitted/tonne) / No	R	Buksti et al. (2015)
Traffic	Number of vehicles / tonne of FW	T	Kijak & Moy (2004)

In order to decide which social indicators to include in Table 8-10, a study was carried out to analyse common social indicators used to assess waste management practices. For this purpose, the following papers were reviewed and used to complete a list of social ramifications: Kijak & Moy (2004), Hung et al. (2006), Hung et al. (2007), Su et al. (2010), Thyberg & Tonjes (2015), Vučijak et al. (2015) and Chong et al. (2016). Subsequently, when reviewing published research on social considerations from the five FWMSs, the indicators found were compared against the list created with the aforementioned papers. Providing the social ramifications generated by the FWMS was in this list, they were added to Table 8-10.

'NIMBY (Not In My Back Yard) syndrome' in this context refers to the opposition by citizens of treating FW near their homes. It has been assumed that NIMBY do not affect redistribution for human consumption or animal feeding, and it would occur only in waste management plants, i.e. when using anaerobic digestion, composting and thermal treatment with energy recovery. Clearly, the effect of NIMBY in these examples is also different: presumably thermal treatments would generate a more negative social impact than anaerobic digestion.

'Feeding people' in this context refers to the number of people fed for a charitable purpose, e.g. food consumed by people in need or used in charitable activities, such as fundraising or raising-awareness events.

The social indicator 'traffic' in this context refers to the social ramifications of a traffic increase, for instance delays, noise and perturbations to citizens. The environmental impacts generated due to transportation of FW are considered environmental indicators only and are included in Table 8-6.

8.4 Chapter summary

This chapter has presented a procedure to optimise industrial FWM. A terminology and FWMMP has been defined, which includes the description and identification of attributes: parameters, variables, factors and indicators to model FW types and FWMSs. The quantitative FW parameters complement the qualitative FW parameters presented in the previous chapter. The assessment of the attributes presented in this chapter makes possible a quantitative estimation of the potential impacts of FWM to the economy, environment and society. Although the FWMMP presents a great level of detail and allows a precise estimation of results from FWM, the FWMMP is flexible and its user can add or remove attributes to adapt it to their specific needs.

Due to the complexity of the FWMMP, it may be difficult for some users to apply the procedure presented in this chapter. In the next chapter, an analysis of the relationships between attributes is presented, which simplifies the use of the FWMMP. The practicality of the approach is tested in Chapter 10.

CHAPTER 9 ANALYSIS OF INFORMATION FLOWS FOR FOOD WASTE MANAGEMENT

9.1 Introduction

This chapter analyses the attributes presented in Sections 7.4 and 8.3 in order to identify relationships between them, revealing the dependencies between attributes and identifying which attributes must be defined in order to obtain the information pursued (i.e. sustainability implications of FWM). The end of the chapter describes a methodology to determine the attributes needed to assess unknown attributes and the optimal order of the assessment. The sequence of the application of the different tools explained in this chapter can be seen in Figure 9-1.

9.2 Relationships between attributes: building the Relationships Matrix

In order to model FWM, an analysis of the relationships between the different parameters, variables, factors and indicators presented in Chapter 8 is necessary to understand the dependencies between attributes. This analysis is also needed to determine which attributes are needed to determine the values of unknown attributes. For instance, there is a relationship between the 'carbohydrate content of FW' and the 'methane content of biogas' obtained from anaerobic digestion, since FW composition affects the yield of the digestion process and the proportion of products obtained. In this example, 'carbohydrate content' is an attribute needed to estimate the outputs generated (such as 'methane content of biogas') from anaerobic digestion, which are initially unknown.

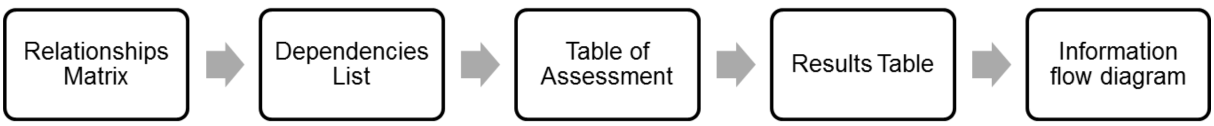


Figure 9-1. Integration of tools to obtain information flow diagrams

Defining all relationships between all variables is largely complex due to a number of reasons. Firstly, because of the number of attributes: 175 attributes were identified and listed in Chapter 8. The relationship between each attribute and all other attributes was assessed, thus $(175^2–175)/2$ = 15,225 relationships between pairs of attributes were analysed and listed in the Relationships Matrix. Secondly, each FWMS presents distinctive relationships. For instance, presence of 'hazardous materials' has an effect on 'management costs' for FWMSs such as anaerobic digestion and composting, since those materials may have to be removed or treated before the process starts. However, for redistribution for human consumption, it was assumed that 'hazardous materials' do not affect the cost of managing the FW, since its presence is sufficient to discard this FWMS. All situations in which a relationship occurred to only some of the FWMSs are explained in Section 9.3.

Furthermore, there are different types of relationships between two attributes, as explained below:

- No relationship: both attributes assessed lack of any dependency to each other. For example, the concentration of 'volatile solids' in FW and the 'distance to transport FW' are not related, i.e. in order to calculate the value of one attribute the other one is not needed.
- Indirect relationship: there is no a mathematical connection between both attributes, although one attribute indirectly affects the possible values of the other attribute. This can occur when the value of one variable limits the use of a FWMS, and therefore the value of the second attribute is affected. For example, 'energy value' is only needed for animal feeding, and the use of animal feeding can be restricted by the 'edibility' and 'state' of FW. Although neither 'edibility' nor 'state' are needed to calculate the 'energy value' of FW, their values can restrict the use of FW for animal feeding and therefore the need to assess 'energy value'.
- Direct relationship: both attributes assessed are related, i.e. in order to calculate the value of one attribute the value of the other one is needed. For example, 'protein content' of FW is needed to estimate the 'nitrogen content' obtained in the composted material after the composting process.

Due to the impracticality of assessing indirect relationships within this research, only direct relationships have been identified. The presence or absence of relationships between attributes has been represented in a 175x175 matrix with 30,450 relationships, since relationships 'attribute A' → 'attribute B' and 'attribute B' → 'attribute A' have been considered as they represent different dependencies. The complete Relationships Matrix has not been included in the thesis due to size limitations, although two sections in Figure 9-2 and Figure 9-3 are provided as examples. The relationships were identified based on the author's knowledge about the FWMSs assessed.

In Figure 9-2, it can be seen that 'inorganic content and composition' affects all environmental impact to air indicators listed, since presence of different inorganic compounds can largely affect the performance (hence, the composition of gases obtained) of FWMSs. However, 'other organic compounds' have an effect in most compounds that can be created during treatment of FW, but not on the release to the atmosphere of inorganic substances such as As, Cd and Hg, since their presence in the gases generated as suspended particles must be explained due to their original presence in FW.

In Figure 9-3 it can be seen that nearly the same attributes affect 'quantity of food redistributed' and 'quantity of animal feed produced', since both factors mainly depend on 'production or flow rate', 'edibility' and 'state', and the attributes which depend on 'edibility' and 'state'. However, 'quantity of food redistributed' is also affected by 'treatment' and 'quantity of animal feed produced' by 'packaging' and 'stage of the supply chain', as justified in Section 7.4.

Relationships between food waste management attributes

						Food-waste parameters						
	A	B	C	D	R	S	T	U	V	W	X
					Primary parameters						
					Vitamin content and composition	Other organic compounds	Inorganic content and composition	Moisture content	Biological hazard	pH	Particle size
71			Air	Total emissions to air	✓	✓	✓	✓	✓	×	×
72				CO_2	✓	✓	✓	✓	✓	✓	✓
73				CH_4	✓	✓	✓	✓	✓	✓	✓
74				N_2O	✓	✓	✓	✓	✓	✓	✓
75				NOx	✓	✓	✓	✓	✓	✓	✓
76				NMVOC	✓	✓	✓	✓	✓	✓	✓
77				Total organic carbon (TOC)	✓	✓	✓	✓	×	×	×
78				NH_3	✓	✓	✓	✓	✓	✓	✓
79				SOx	✓	✓	✓	✓	✓	✓	✓
80				HCl	✓	✓	✓	✓	✓	✓	✓
81				Dioxins, furans, PAH, PCBs and products alike	✓	✓	✓	✓	✓	✓	✓
82				H_2S	✓	✓	✓	✓	✓	✓	✓
83				CO	✓	✓	✓	✓	✓	✓	✓
84				Dust	✓	✓	✓	✓	×	×	×
85				PM<10	✓	✓	✓	✓	✓	✓	✓
86				PM<2.5	✓	✓	✓	✓	×	×	×
87				As	×	×	✓	×	×	×	×
88				Cd	×	×	✓	×	×	×	×
89				Hg	×	×	✓	×	×	×	×
90				Zn	×	×	✓	×	×	×	×
91				Cr	×	×	✓	×	×	×	×
92				Ni	×	×	✓	×	×	×	×
93				Pb	×	×	✓	×	×	×	×
94				Cu	×	×	✓	×	×	×	×

Figure 9-2. Example 1: 24x7 matrix showing an analysis of 168 relationships between some quantitative primary FW parameters and environmental impact to air indicators. A green tick denotes presence of relationship and a red cross absence of relationship

	A	B	C	D	BG	BH	BI	BJ	BK	BL	BM
1	**Relationships between food waste management attributes**				**Performance factors**						
2											
3											
4					Quantity of food redistributed	Quantity animal feed produced	Biogas production rate	[CH4] in biogas	Digestate flow rate	Digestate composition	Compost production rate
5	**Food-waste parameters**	**Qualitative**		Edibility	✓	✓	✗	✗	✗	✗	✗
6				State	✓	✓	✗	✗	✗	✗	✗
7				Origin	✗	✓	✗	✗	✗	✗	✓
8				Complexity	✗	✓	✗	✗	✗	✗	✓
9				Animal-material presence	✗	✓	✗	✗	✗	✗	✓
10				Treatment	✓	✗	✗	✗	✗	✗	✗
11				Packaging	✗	✓	✗	✗	✗	✗	✗
12				Packaging biodegradability	✗	✗	✓	✓	✓	✓	✓
13				Stage of the supply chain	✗	✓	✗	✗	✗	✗	✗
14		**Quantitative**	**Primary parameters**	Production or flow rate	✓	✓	✓	✗	✓	✗	✓
15				Carbohydrate content and composition	✗	✗	✓	✓	✓	✓	✓
16				Fat content and composition	✗	✗	✓	✓	✓	✓	✓
17				Protein content and composition	✗	✗	✓	✓	✓	✓	✓
18				Vitamin content and composition	✗	✗	✓	✓	✓	✓	✓
19				Other organic compounds	✓	✓	✓	✓	✓	✓	✓
20				Inorganic content and composition	✓	✓	✓	✓	✓	✓	✓
21				Moisture content	✗	✗	✓	✓	✓	✓	✓
22				Biological hazard	✓	✓	✓	✓	✓	✓	✓
23				pH	✗	✗	✓	✓	✓	✓	✓
24				Particle size	✗	✗	✓	✓	✓	✓	✓
25			**Secondary parameters**	Density	✗	✗	✓	✓	✓	✓	✓
26				Hazardous materials	✓	✓	✓	✓	✓	✓	✓
27				Energy value	✗	✗	✗	✗	✗	✗	✗
28				Volatile solids (VS)	✗	✗	✓	✓	✗	✗	✗
29				Total solids (TS)	✗	✗	✗	✗	✓	✓	✓
30				Total Kjeldahl nitrogen (TKN)	✗	✗	✓	✓	✓	✓	✓
31				Total ammonia nitrogen (TAN)	✗	✗	✓	✓	✓	✓	✗
32				Chemical oxygen demand (COD)	✗	✗	✓	✓	✓	✓	✗
33				C:H:O:N:P:S ratio	✗	✗	✓	✓	✓	✓	✗

Figure 9-3. Example 2: 29x7 matrix showing an analysis of 203 relationships between performance factors and FW parameters

If a relationship between two attributes exists only for some FWMSs and not for others, it was considered that the relationship exists. For instance, 'biological hazard' and 'economic value of solid material' are related for anaerobic digestion and composting, since biologically contaminated digestate or compost may not be spread on land. However, for thermal treatment with energy recovery, this is not relevant when the char is used as fuel. Since there are some situations in which this relationship exists, it was considered that both attributes were related in the Relationships Matrix.

'Other organic compounds' include hydrocarbons and organic substances with oxygen (e.g. ethanol), nitrogen (e.g. nitrogen fertilizers such as urea), phosphorus, (e.g. adenosine triphosphate produced by microorganisms), sulphur (e.g. coenzyme A) and chlorine (e.g. dioxins). Consequently, the presence of 'other organic compounds' may affect the presence of the aforementioned elements in impacts to air, water and soil.

Possible chemical reactions have been considered in this analysis. For instance, nitrogen present in FW (and measured with 'total Kjeldahl nitrogen' and/or 'total ammonia nitrogen') can create substances such as N_2O, NOx, NH_3 and NO_3^-, which can pollute air, water or soil.

Hence, when assessing chemical compounds that can be formed during the process (e.g. NH_3), the precise initial composition of FW is needed (i.e. content of carbohydrate, fat, protein and other molecules and elements) since this affects the generation of new substances. On the other hand, if it can be assumed that the substances were present in the initial FW sample and they have not been altered, only the relevant primary quantitative FW parameters must be assessed. For instance, in order to assess impact of nickel in the soil, only the 'inorganic content and composition' must be assessed as a primary quantitative FW parameter, since nickel was not created during the FWM process.

Both 'volatile solids' and 'total solids' depend on the initial solid content of FW, and therefore on the content of carbohydrate, fat, protein and other molecules and elements. Despite the fact that 'moisture content' does not directly affect the 'total solids' of FW, a relationship has been considered, since 'total solids' of FW is typically calculated measuring the total mass and subtracting the mass of volatile compounds (which is mainly water) after drying at a high temperature. Therefore, it is considered that 'moisture content' can be a parameter needed to assess 'total solids' of FW.

'Type of equipment available' may prevent the emission of substances to air, water and soil. For instance, scrubbers reduce the release of substances to the atmosphere, and filters and gratings reduce the emission of substances and materials to water. Consequently, a relationship between 'type of equipment available' and a release of substances to air, water and soil has been considered.

'Dioxins, furans, PAH, PCBs and products alike' are not produced during anaerobic digestion or composting, although these compounds have been found in waste treatment plants. According to Brändli, Kupper, et al. (2007), the cause of this was activities indirectly related to the waste treatment, such as fossil fuel combustion and vehicles emissions. It has been assumed that, when these compounds are found in the soil, they have been deposited from air, where they were released because of the aforementioned reasons. Because of this, environmental impacts to soil such as 'dioxins, furans, PAH, PCBs and products alike' are related to 'distance to transport FW', since longer distances generates higher emissions of those compounds that precipitate on the soil.

Management of solid and water residues also generates relevant air emissions. For instance, digestate from anaerobic digestion causes significant impacts to air, such as release of ammonia and methane (Whiting & Azapagic 2014). For thermal treatments with energy recovery, air emissions were also considered for the management of char, since char is widely used as a fuel, releasing substances to the atmosphere when it is burnt. Char, particularly biochar, can alternatively be used as a soil amendment, and therefore in these cases there is a relationship between char and nutrient content of different elements in soil. Yet, the primary quantitative FW parameter 'ash' is considered to impact only water and soil, and not air, since ash is the solid that remains after the thermal treatment.

For 'total emissions to air' and 'solid residue flow rate', all attributes that affect the output generated have been considered as a relationship. For instance, FW composition affect the type and quantity of gases released during the composting process. However, for 'wastewater flow', only the causes of generating a specific quantity of wastewater have been considered, e.g. 'production or flow rate' of FW. A modification of the FW composition or the FWM process does not change the quantity of wastewater, but rather the composition of wastewater. For instance, a higher protein concentration in FW would generate a similar wastewater flow from the FWM process, although it can increase quantity of nitrates, ammonia and other substances, or values such as COD or BOD of the wastewater.

The presence of all elements classified as an environmental indicator has been assessed for each FW parameter. For instance, sulphur ('S') is present in some proteins and vitamins; consequently 'protein content and composition' and 'vitamin content and composition' are related to 'S' in environmental impacts to water. Similarly, all elements classified as an environmental indicator have been assessed to elucidate whether they can be harmful for humans and/or the environment. For instance, mercury ('Hg') in air, water or soil is clearly noxious and therefore is related to 'hazardous materials'.

'Electrical conductivity', as an indicator for environmental impact to soil, is related with the final inorganic and moisture content in the residue after the FWM process. The final inorganic and moisture content is related to the initial value of these attributes in FW and process and company variables such as 'process time', 'temperature' and 'additives and catalysts'.

'Management cost' is related to performance factors regarding quantity of outputs generated, such as 'quantity of animal feed produced', and 'biogas production rate', because higher production rate generally increases costs, for instance storage costs.

As explained in Section 8.3.4.3, the social indicator 'traffic' refers to the social ramifications of a traffic increase, such as delays, noise and perturbations to citizens, and not to emissions generated during transportation of FW. Additionally, 'noise' is affected by the amount of FW to treat, FW processing (e.g. type and volume of equipment, stirring), quantity of materials produced and traffic.

9.2.1 Combination of attributes

Due to the considerable size of the Relationships Matrix, a number of actions have been taken to reduce its size and make it easier and more efficient to use. Firstly, all attributes and their relationships have been checked to combine attributes which are related to the same attributes. For instance, Figure 9-4 shows a section of the original Relationships Matrix. It can be seen that, in the section displayed, 'CO_2', 'CH_4', 'NMVOC' and 'PM<10' are related to the same attributes: 'density', 'hazardous materials' and 'volatile solids'. In fact, that similarity is extended to the rest of the Relationships Matrix. Figure 9-5 shows the same section of the Relationships Matrix in which the attributes have been grouped. It can be seen that 'CO_2', 'CH_4', 'NMVOC' and 'PM<10' have been combined in one single attribute, namely 'CO_2, CH_4, NMVOC and PM<10'. This means that, in order to find the relationships of one of the aforementioned attributes, e.g. 'CO_2', the attribute 'CO_2, CH_4, NMVOC and PM<10' must be checked. This combination of attributes allows reducing the size of the Relationships Matrix from a 175x175 matrix with 30,450 relationships to a 136x136 matrix with 18,360 relationships.

	A	B	C	D	Y	Z	AA	AB	AC	AD	AE
1	**Relationships between food waste management attributes**										
2					**uantitative**						
3											**Seconda**
4					Density	Hazardous materials	Energy value	Volatile solids (VS)	Total solids (TS)	Total Kjeldahl nitrogen (TKN)	Total ammonia nitrogen (TAN)
71				Total emissions to air	✗	✓	✗	✓	✗	✓	✓
72				CO_2	✓	✓	✗	✓	✗	✗	✗
73				CH_4	✓	✓	✗	✓	✗	✗	✗
74				N_2O	✓	✓	✗	✓	✗	✓	✓
75				NOx	✓	✓	✗	✓	✗	✓	✓
76				NMVOC	✓	✓	✗	✓	✗	✗	✗
77				Total organic carbon (TOC)	✓	✓	✗	✓	✗	✗	✗
78				NH_3	✓	✓	✗	✓	✗	✓	✓
79				SOx	✓	✓	✗	✓	✗	✗	✗
80				HCl	✓	✓	✗	✓	✗	✗	✗
81				Dioxins, furans, PAH, PCBs and products alike	✓	✓	✗	✓	✗	✗	✗
82			Air	H_2S	✓	✓	✗	✓	✗	✗	✗
83				CO	✓	✓	✗	✓	✗	✗	✗
84				Dust	✓	✓	✗	✓	✗	✗	✗
85				PM<10	✓	✓	✗	✓	✗	✗	✗
86				PM<2.5	✓	✓	✗	✓	✗	✗	✗
87				As	✗	✓	✗	✓	✗	✗	✗
88				Cd	✗	✓	✗	✓	✗	✗	✗
89				Hg	✗	✓	✗	✓	✗	✗	✗
90				Zn	✗	✓	✗	✓	✗	✗	✗
91				Cr	✗	✓	✗	✓	✗	✗	✗
92				Ni	✗	✓	✗	✓	✗	✗	✗
93				Pb	✗	✓	✗	✓	✗	✗	✗
94				Cu	✗	✓	✗	✓	✗	✗	✗

Figure 9-4. 24x7 matrix showing an analysis of 168 relationships between some secondary quantitative FW parameters and environmental impact to air indicators

Relationships between food waste management attributes

	A	B	C	D	Y	Z	AA	AB	AC	AD	AE
2					Quantitative						
3					Seconda						
4					Density	Hazardous materials	Energy value	Volatile solids (VS)	Total solids (TS)	Total Kjeldahl nitrogen (TKN)	Total ammonia nitrogen (TAN)
71			Air	Total emissions to air	×	✓	×	✓	×	✓	✓
72				CO_2, CH_4, NMVOC, PM<10	✓	✓	×	✓	×	×	×
73				N_2O, NOx	✓	✓	×	✓	×	✓	✓
74				Total organic carbon (TOC), dust, PM<2.5	✓	✓	×	✓	×	×	×
75				NH_3	✓	✓	×	✓	×	✓	✓
76				SOx	✓	✓	×	✓	×	×	×
77				HCl	✓	✓	×	✓	×	×	×
78				Dioxins, furans, PAH, PCBs and products alike	✓	✓	×	✓	×	×	×
79				H_2S	✓	✓	×	✓	×	×	×
80				CO	✓	✓	×	✓	×	×	×
81				As, Cd, Hg, Zn, Cr, Ni, Pb, Cu	×	✓	×	✓	×	×	×

Figure 9-5. 11x7 matrix showing an analysis of 77 relationships between some secondary quantitative FW parameters and environmental impact to air indicators. Indicators with same relationships have been grouped

9.2.2 Streamlined Relationships Matrix

In order to further reduce the size of the Relationships Matrix, an alternative version has been developed: the Streamlined Relationships Matrix. Since the stage of the FWMMP with more attributes is ‘environmental indicators’ (Section 8.3.4.1), this has been reduced to include only the most relevant indicators: ‘total emissions to air’, ‘CO_2’ and ‘CH_4’ for environmental impacts to air; ‘wastewater flow’, ‘chemical oxygen demand’ and ‘total suspended solids’ for environmental impacts to water; and ‘solid residue flow rate’, ‘nutrient content: N’, ‘nutrient content: P’ and ‘nutrient content: K’ for environmental impacts to soil. The selection of those indicators was undertaken considering the most commonly used indicators to assess environmental impacts of FWM in the literature.

Similarly, the list of process and company variables has been reduced to include only those more relevant. Accordingly, only the following company and process variables have been included in the Streamlined Relationships Matrix: ‘distance to transport food waste’, ‘volume of equipment available’, ‘temperature’, ‘process time’, ‘pH’, ‘organic loading rate (OLR)’, ‘oxygen concentration / air ratio’ and ‘pressure’.

A section of the Streamlined Relationships Matrix showing these attributes can be seen in Figure 9-6. The dimension of the Streamlined Relationships Matrix is 73x73, and contains 5,256 relationships.

Relationships between food waste management attributes

				A	B	C	D	BL	BM	BN	BO	BP	BQ	BR
1–3								**erformance factors**						
4								Digestate composition	Compost production rate	Compost composition	Gas flow rate	Lower heating value of gas	Char production rate	Heating value of char
71					Environmental	Air	Total emissions to air	✗	✓	✗	✓	✗	✓	✗
72							CO_2	✓	✓	✓	✓	✓	✓	✓
73							CH_4	✓	✓	✓	✓	✓	✓	✓
74						Water	Wastewater flow	✗	✓	✗	✗	✗	✓	✗
75							Chemical oxygen demand (COD)	✓	✓	✓	✗	✗	✓	✓
76							Total suspended solids (TSS)	✓	✓	✓	✗	✗	✓	✓
77						Soil	Solid residue flow rate	✗	✓	✗	✗	✗	✓	✗
78							Nutrient content: N	✓	✓	✓	✗	✗	✓	✓
79							Nutrient content: P	✓	✓	✓	✗	✗	✓	✓
80							Nutrient content: K	✓	✓	✓	✗	✗	✓	✓

Figure 9-6. 10x7 matrix showing an analysis of 70 relationships between some performance factors and environmental indicators

9.2.3 Dependencies List

Once all relationships between attributes have been found, there is a need to assess the dependencies between attributes. For instance, it had been determined that 'CO_2 emissions' and 'distance to transport FW' are related, but not which attribute depends on the other. In this example, 'CO_2 emissions' depend on 'distance to transport FW', since the value of 'distance to transport FW' is needed to find the value of 'CO_2 emissions', and not the other way round. All dependencies for each relationship have been assessed and listed in the Dependencies List, in which each attribute is listed at the top of each column, and the attributes which depend on it are underneath. This procedure has been completed for all 136 attributes which were obtained after combining attributes (Section 9.2.1). An example of a section of the Dependencies List can be seen in Figure 9-7. For instance, in the example provided, the first column means that 'state', 'quantity of food redistributed' and 'quantity of animal feed produced' depend on 'edibility'.

	E	F	G	H	I
1	**Food-waste parameters**				
2	**Qualitative**				
3					
4	Edibility	State	Origin	Complexity	Animal-material presence
5	State	Biological hazard	Animal-material presence	Animal-material presence	Temperature
6	Quantity of food redistributed	Hazardous materials	Temperature	Temperature	Pre-treatment
7	Quantity animal feed produced	Quantity of food redistributed	Pre-treatment	Pre-treatment	Quantity animal feed produced
8		Quantity animal feed produced	Quantity animal feed produced	Quantity animal feed produced	Compost production rate
9			Compost production rate	Compost production rate	Compost composition
10			Compost composition	Compost composition	

Figure 9-7. Section of the Dependencies List for redistribution for human consumption showing dependencies to five attributes

Five Dependencies Lists have been created, one for each FWMS under consideration: redistribution for human consumption, animal feeding, anaerobic digestion, composting and thermal treatment with energy recovery (as justified in Section 7.5.1.1). In each Dependencies List the attributes relevant to the FWMS assessed have been highlighted in red (as in Figure 9-7), because only those attributes are needed to model that FWMS according to the analysis presented in Chapter 8. For instance, 'quantity of animal feed produced' is not needed to assess redistribution for human consumption and therefore is not highlighted in Figure 9-7.

Even when the attributes are relevant for the FWMS assessed, there are some situations in which a relationship can be discarded. For instance, 'other compounds of interest' were considered relevant for redistribution for human consumption, since they may include hazardous materials. However, for anaerobic digestion, composting and thermal treatment with energy recovery 'other compounds of interest' is also needed for attributes such as 'total emissions to air', since FW composition affects the gases generated from the processes. Therefore, each dependency from each FWMS was assessed independently in order to discard non-necessary dependencies. As a result, discarded dependencies have been listed in Table 9-1.

Dependencies have been built between attributes of each stage and prior stages from the Figure 8-1. For example, secondary quantitative FW parameters may depend on quantitative primary and qualitative FW parameters, performance factors may depend on process and company variables and FW parameters, and environmental indicators may depend on performance factors. However, process and company variables cannot depend on performance factors. The dependencies have also been assessed within the same stage, e.g. 'process time' needed to anaerobically digest FW may depend on the 'volume of equipment available', since a larger vessel would allow more FW to be treated in a certain amount of time.

Defining dependencies between attributes within the same stage is more intricate than between attributes from different stages, since deciding which of both attributes depend on the other attribute can be complex and unclear. When that happened, an assessment of each situation was carried out on a case-by-case basis in order to define the most common or sensible dependency between both attributes. For instance, it was considered that the 'temperature' in a thermal treatment with energy recovery affects the 'air ratio' used in the incinerator to obtain the final products pursued.

Table 9-1. Discarded dependencies from the Relationships Matrix

FWMS	Attribute on which other attributes depend	Dependent attribute
Redistribution for human consumption	Other organic compounds	Density, total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Inorganic content and composition	Density, total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Biological hazard	Density, total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5, management cost
	Density	CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Hazardous materials	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5, management cost
Animal feeding	Carbohydrate content and composition	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Fat content and composition	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Protein content and composition	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Other organic compounds	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Inorganic content and composition	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Biological hazard	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Density	CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5
	Hazardous materials	Total emissions to air, CO_2, CH_4, NMVOC, PM<10, N_2O, NOx, TOC, dust, PM<2.5

9.3 Information flowcharts to model FWMSs

The five Dependencies Lists explained in Section 9.2.3 have been used to draw information flowcharts which show dependencies between all attributes relevant to each FWMS. The attributes have also been classified according to the FWMMP (Chapter 8). The information flowcharts can be seen in Figure 9-8 to Figure 9-12. It must be noted that the full version of the Relationships Matrix with combined attributes (Section 9.2.1) was used for Figure 9-8 and Figure 9-9, but due to size limitations the Streamlined Relationships Matrix (Section 9.2.2) was used for Figure 9-10 to Figure 9-12.

The information flowcharts can be used in different ways. An attribute can be chosen and it can be elucidated which attributes depend on it following the arrows, e.g. in Figure 9-8, 'biological hazard' is needed to assess 'hazardous materials' and 'quantity of food redistributed'. Alternatively, an attribute can be chosen and it can be elucidated which attributes are needed to assess that attribute following the arrows backwards, e.g. in Figure 9-8, 'quantity of food redistributed', 'distance to transport FW' and 'production or flow rate' are needed to assess 'management cost'.

It must be noted that in for Figure 9-10 to Figure 9-12 chemical oxygen demand (COD) and total suspended solids (TSS) have been combined, since in the streamlined version of these three information flowcharts their dependencies are identical.

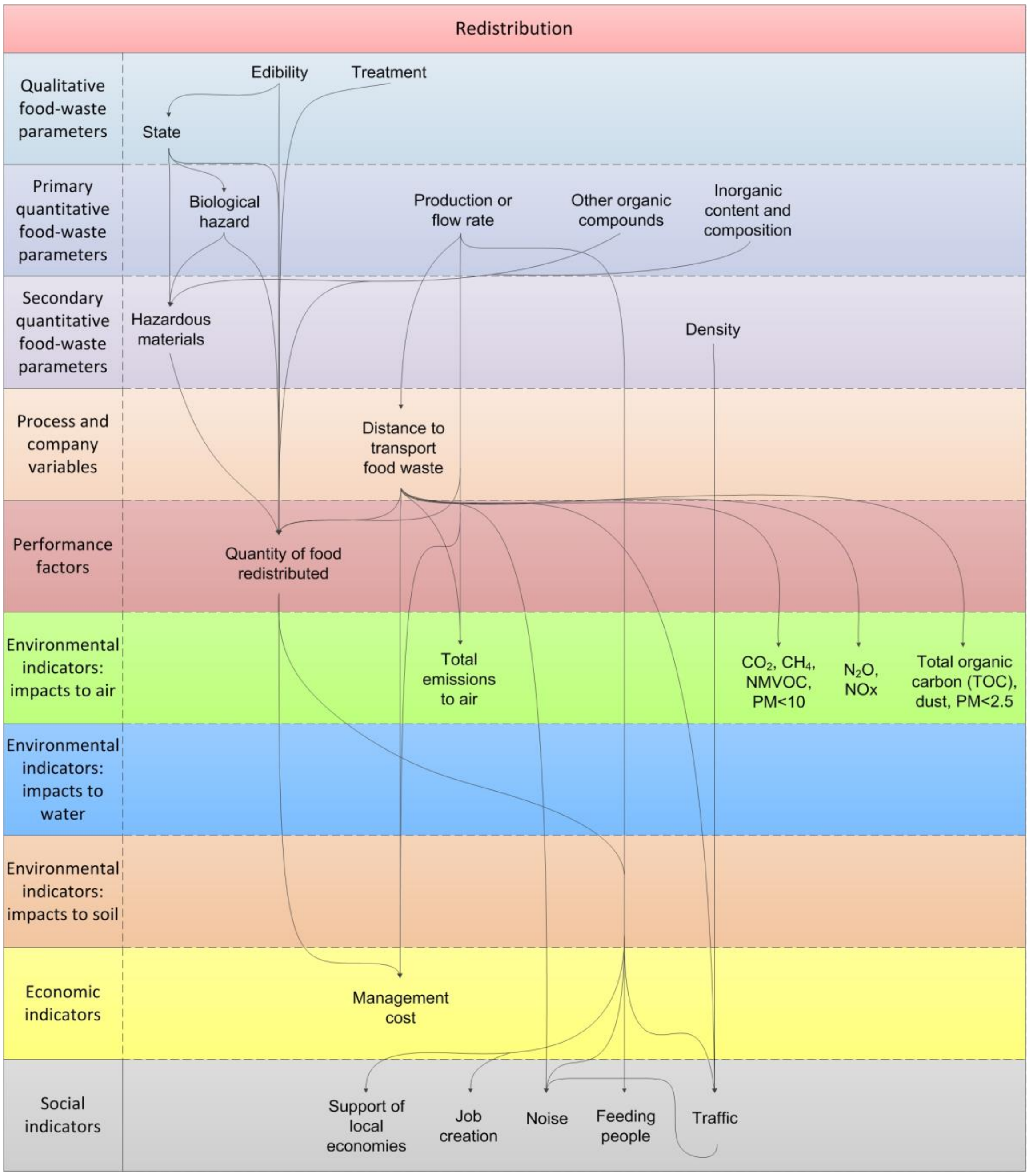


Figure 9-8. Information flowchart for redistribution for human consumption

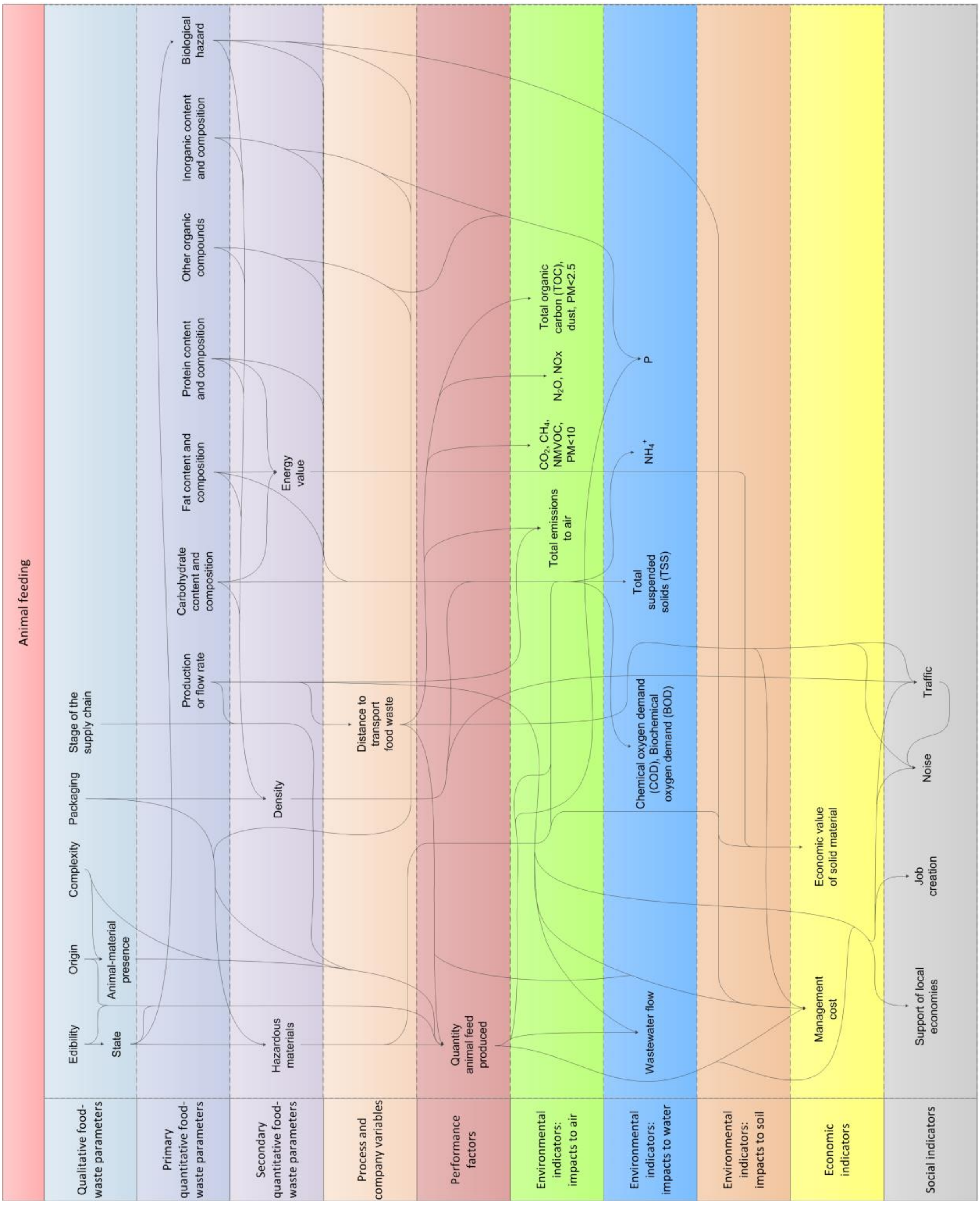


Figure 9-9. Information flowchart for animal feeding

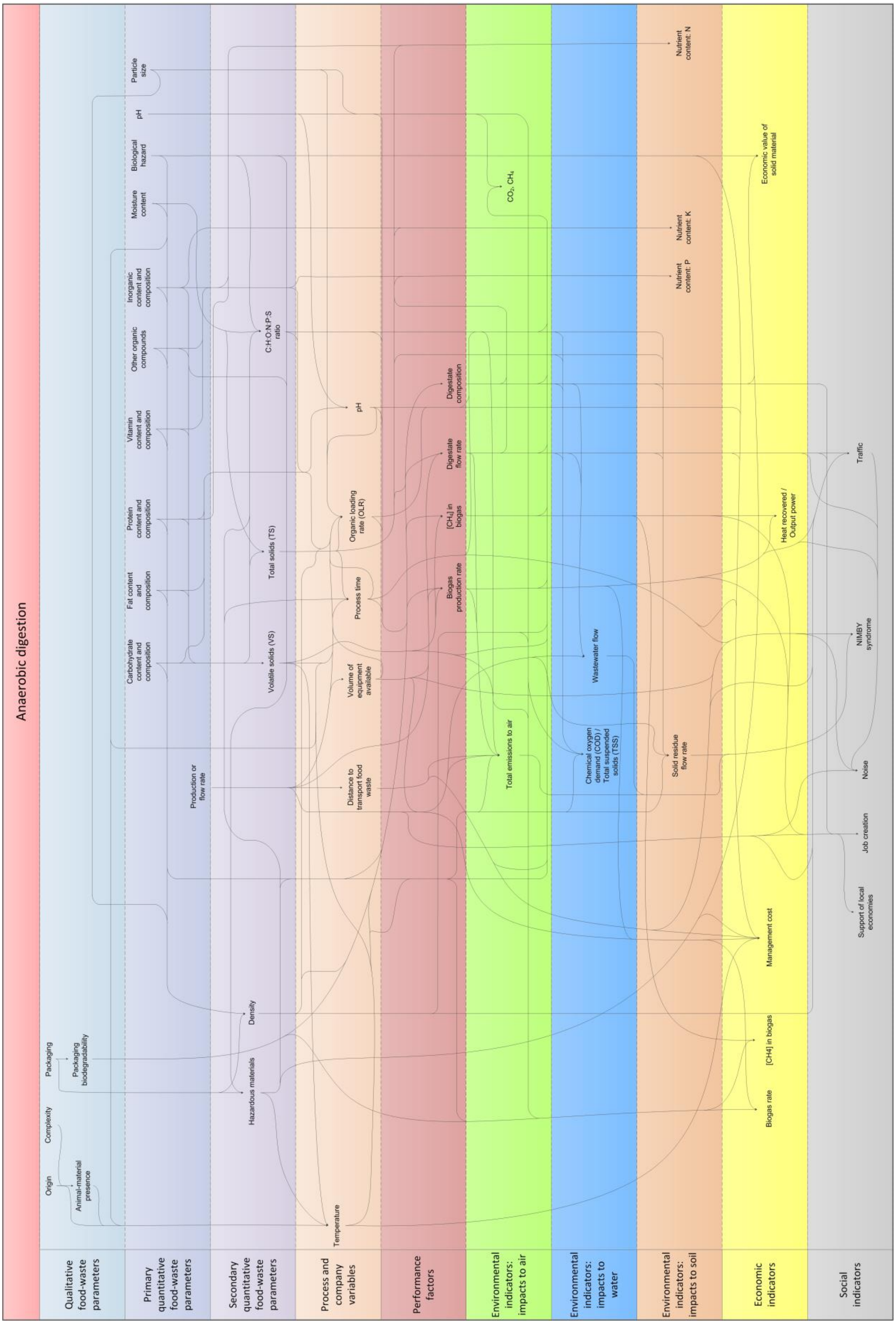


Figure 9-10. Information flowchart for anaerobic digestion

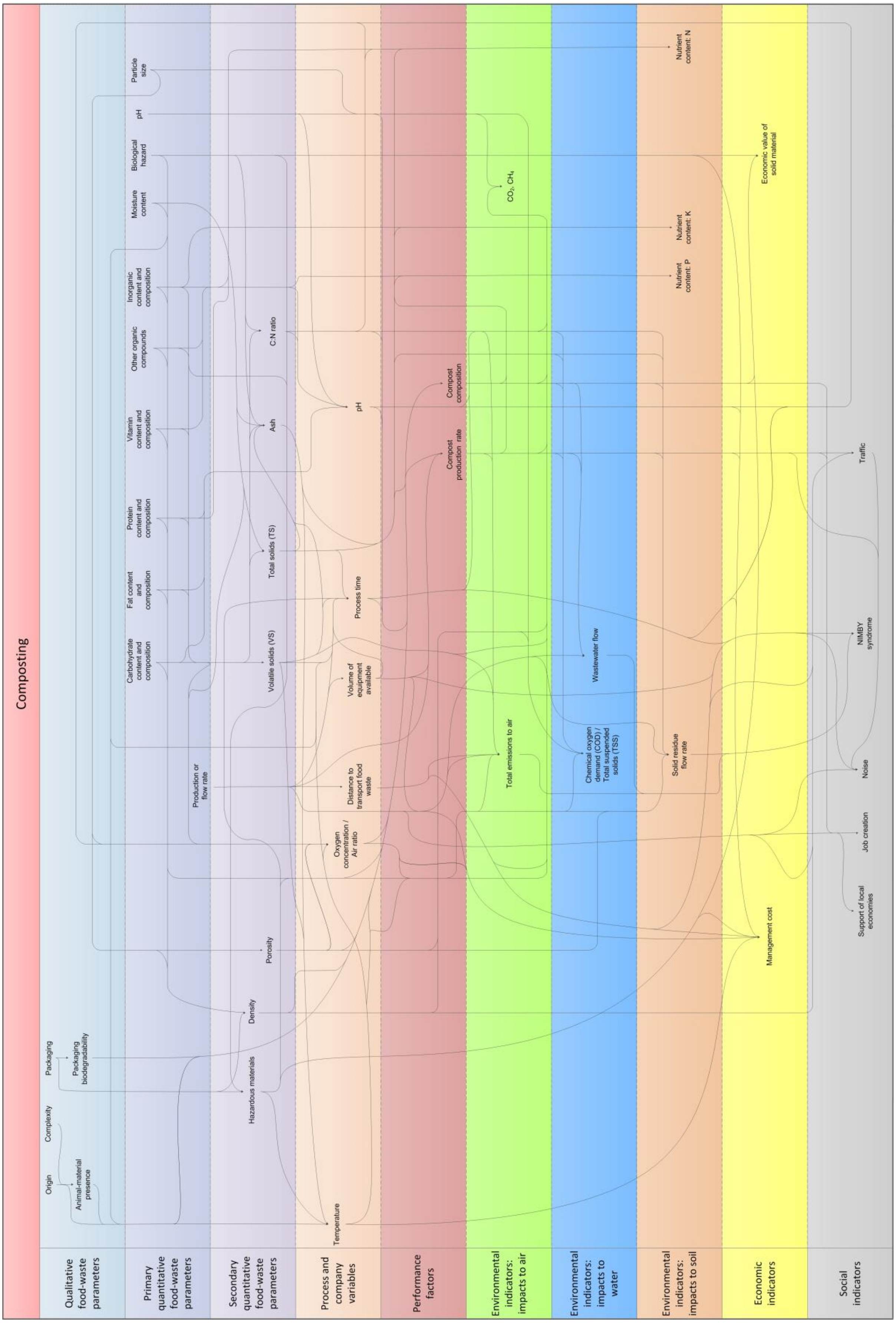


Figure 9-11. Information flowchart for composting

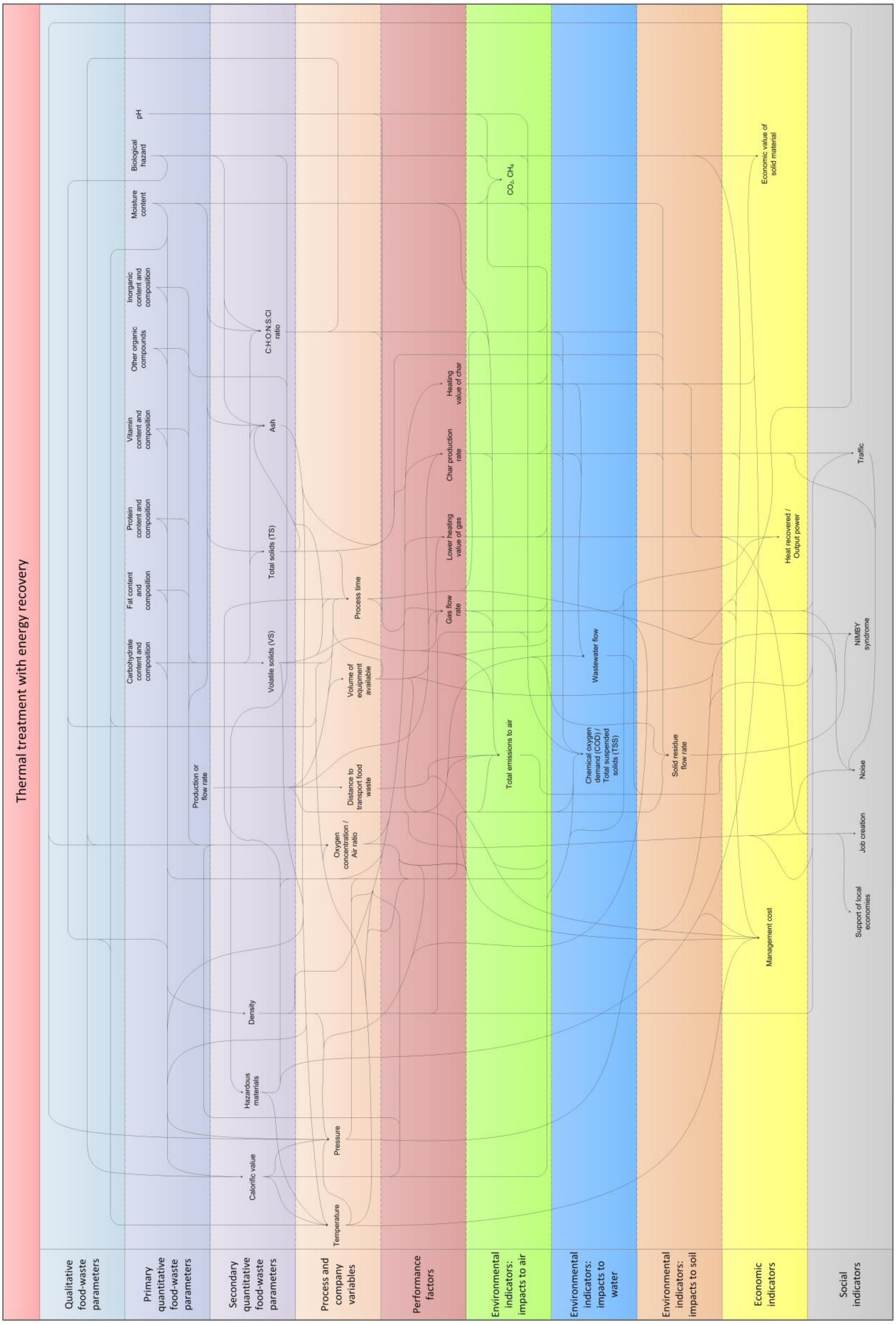


Figure 9-12. Information flowchart for thermal treatment with energy recovery

9.4 Methodology to assess information flows

This section explains a methodology that can be used to determine the attributes needed to assess unknown attributes and the optimal order of the assessment. This methodology has been designed such that it can be used by any company or suitably knowledgeable person who manages FW, referred to hereinafter as the 'user'. The methodology should be applied every time a new FW is identified or the known/unknown attributes change.

The main tool for this methodology is the Table of Assessment. The Table of Assessment is built from the Dependencies List, as explained in the following subsection. Next, the Table of Assessment is used to obtain the Results Table, which can be subsequently used to draw information flows diagrams, as explained in Section 9.4.2.

9.4.1 Building the Table of Assessment

The user starts the assessment using the Table of Assessment, which is a spreadsheet that contains one sheet for each FWMS. In each of the sheets, all attributes needed to model FWM for that particular FWMS are listed, which have been identified using the tables of Section 8.3. Additionally, for each attribute identified the attributes on which it depends were determined, which were added to a 'List of attributes needed' in the spreadsheet, as explained below. An example of a section of the Table of Assessment can be seen in Table 9-2.

Table 9-2. An example of a section of the Table of Assessment for redistribution for human consumption

Category of attribute to assess	Attribute to assess	List of attributes needed	
Qualitative food-waste parameters	Edibility		
	State	Edibility	
	Treatment		
Primary quantitative food-waste parameters	Production or flow rate		
	Biological hazard	State	
	Other organic compounds		
	Inorganic content and composition		
Secondary quantitative food-waste parameters	Hazardous materials	State	Other organic compounds
	Density		
Process and company variables	Distance to transport food waste	Production or flow rate	
Performance factors	Quantity of food redistributed	Edibility	Treatment
Environmental indicators: impacts to air	Total emissions to air	Distance to transport food waste	Production or flow rate
	CO_2, CH_4, NMVOC, PM<10	Distance to transport food waste	
	N_2O, NOx	Distance to transport food waste	
	Total organic carbon (TOC), dust, PM<2.5	Distance to transport food waste	
Environmental indicators: impacts to water			
Environmental indicators: impacts to soil			
Economic indicators	Management cost	Production or flow rate	Distance to transport food waste
Social indicators	Support of local economies	Production or flow rate	Quantity of food redistributed
	Job creation	Production or flow rate	Quantity of food redistributed
	Noise	Production or flow rate	Quantity of food redistributed
	Feeding people	Production or flow rate	Quantity of food redistributed
	Traffic	Production or flow rate	Quantity of food redistributed

In order to build the 'List of attributes needed', the Dependencies List (Section 9.2.3) was used along with the information flowcharts (Section 9.3) to identify dependencies relevant for each FWMS. The specific methodology used to build the 'List of attributes needed' is depicted in Figure 9-13 and explained in the next page.

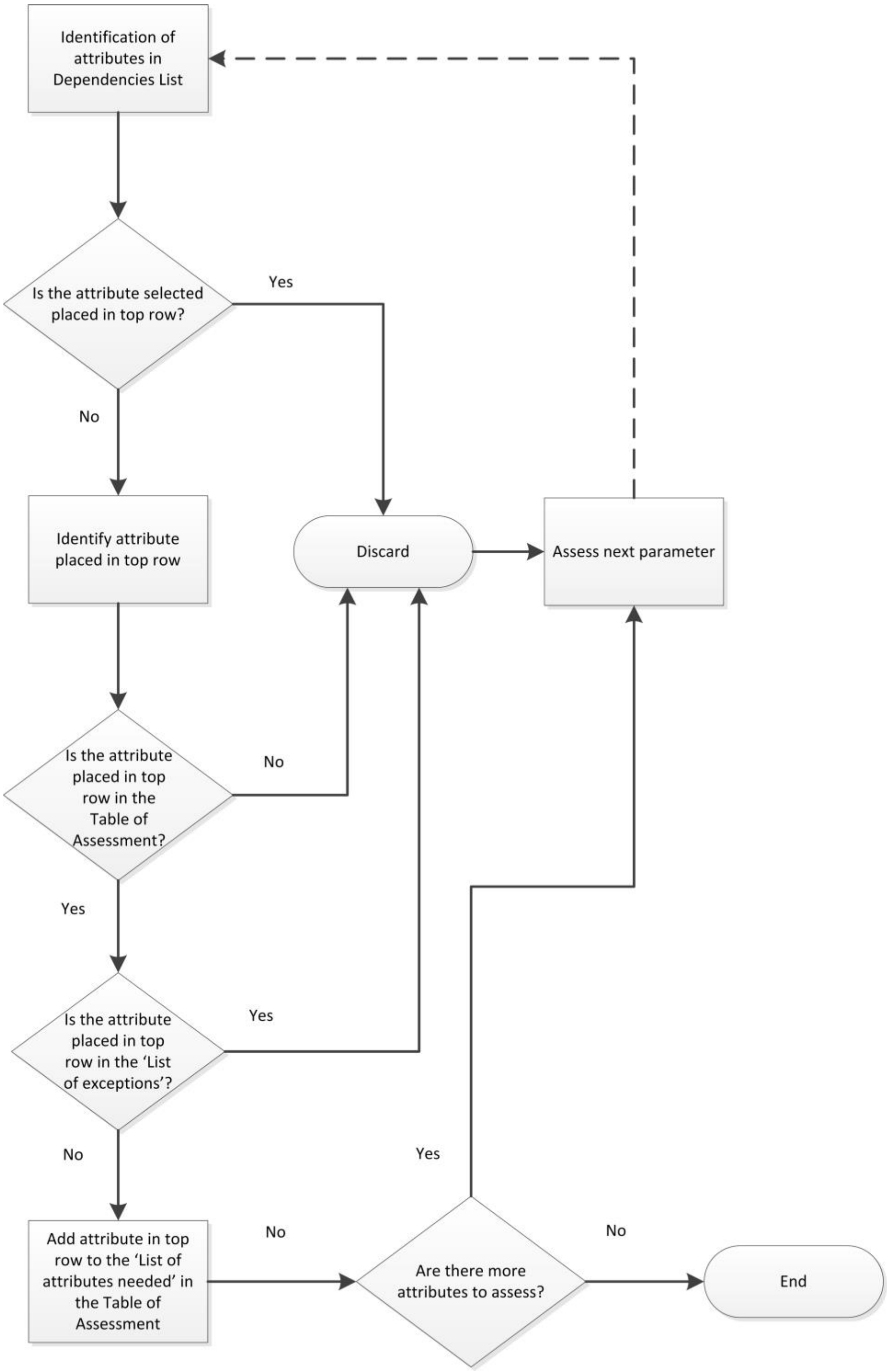


Figure 9-13. Methodology used to build the 'List of attributes needed' in the Table of Assessment

Firstly, each attribute relevant to the FWMS under consideration must be found in the Dependencies List. If the attribute found is in the top row, it must not be assessed, because its position indicates that it does not depend on the value of other attributes. It must be noted that all attributes appear once in the top row, since all attributes and relationships have been assessed, but for this process only the attributes that depend on other attributes are needed.

Secondly, for each time an attribute is found, the attribute in the top row must be identified. However, only those attributes which appear in the Table of Assessment are needed, since this means that the attribute is necessary to model the FWMS under consideration. Additionally, the attribute must be added to the 'List of attributes needed' only if the relationship found is not included in the 'List of exceptions' (Table 9-1). This process should be repeated until all attributes relevant to the FWMS under consideration have been assessed, completing the 'List of attributes needed'.

9.4.2 Using the Table of Assessment to obtain the Results Table and information flow diagrams

Once the 'List of attributes needed' has been built for each FWMS, an analysis must be carried out to define the order of calculation for the different attributes, and what attributes should be used to calculate unknown attributes. The entire process, integrating the research presented in Chapters 7, 8 and 9 is explained below.

The process starts when the user identifies the FW to be analysed according to the definitions provided in Section 7.2. Next, the user assesses the FW using the nine-stage qualitative categorisation (Section 7.4) and the FWMDT (Section 7.5) to identify the most sustainable FWMS. After that, the user must open the Table of Assessment and select the correct sheet, according to the FWMS chosen. The user would see a list of attributes to be assessed, the category to which they belong, and the 'List of attributes needed' in order to assess each attribute. Then, the user has to identify which values of attributes are known (typing 'Y'), unknown (typing 'N') required (typing 'R'), since the user may want to assess only some attributes. An example of a section of the Table of Assessment, with the required information filled in, can be seen in Table 9-3. In this example, the 'production or flow rate', 'density of FW', 'distance to transport FW' and 'quantity of food redistributed' are the only values known by the user. 'Biological hazard', 'hazardous material', 'total emissions to air', 'CO_2', 'CH_4', 'NMVOC', 'PM<10' and 'number of people in need fed' are the unknown variables required by the user. The 'quantity of food redistributed' is also required, but its value is already known by the user as mentioned above.

Table 9-3. An example of a section of the Table of Assessment for Redistribution for human consumption in which the user has determined which values are known (Y), which are unknown (N) and which are required (R). The section of the table is divided into two parts for displaying purposes

Category of attribute to assess	Attribute to assess	Is the value of the attribute known?	Mark the attributes required	List of attributes needed	
Qualitative food-waste parameters	Edibility	N			
	State	N		Edibility	
	Treatment	N			
Primary quantitative food-waste parameters	Production or flow rate	Y			
	Biological hazard	N	R	State	
	Other organic compounds	N			
	Inorganic content and composition	N			
Secondary quantitative food-waste parameters	Hazardous materials	N	R	State	Other organic compounds
	Density	Y			
Process and company variables	Distance to transport food waste	Y		Production or flow rate	
Performance factors	Quantity of food redistributed	Y	R	Edibility	Treatment
Environmental indicators: impacts to air	Total emissions to air	N	R	Distance to transport food waste	Production or flow rate
	CO_2, CH_4, NMVOC, PM<10	N	R	Distance to transport food waste	
	N_2O, NOx	N		Distance to transport food waste	
	Total organic carbon (TOC), dust, PM<2.5	N		Distance to transport food waste	
Environmental indicators: impacts to water					
Environmental indicators: impacts to soil					
Economic indicators	Management cost	N		Production or flow rate	Distance to transport food waste
Social indicators	Support of local economies	N		Production or flow rate	Quantity of food redistributed
	Job creation	N		Production or flow rate	Quantity of food redistributed
	Noise	N		Production or flow rate	Quantity of food redistributed
	Feeding people in need	N	R	Production or flow rate	Quantity of food redistributed
	Traffic	N		Production or flow rate	Quantity of food redistributed

Once the two columns of the Table of Assessment have been completed, the Results Table must be filled in. An example of a Results Table for the example presented in Table 9-3 can be seen in Table 9-4. The user must find all attributes which are both unknown and required, and copy them into the column 'destiny attribute' in the Results Table. Additionally, the attributes from 'List of attributes needed' are copied to 'origin attribute' for each 'attribute to assess' copied to 'destiny attribute'.

Next, the row 'origin attribute' for each 'destiny attribute' is assessed to find unknown attributes. If only known attributes, or no attributes are found in 'origin attribute', 'destiny attribute' receives a value n = 1, which means that the attribute must be assessed in first place. For instance, in Table 9-4 'edibility', 'other organic compounds', 'inorganic content and composition', 'total emissions to air', 'CO_2, CH_4, NMVOC, PM<10' and 'feeding people' receive a value n = 1.

Each unknown attribute found in 'origin attribute' must be assessed and added to the Results Table as a new 'destiny attribute' (along with its correspondent attributes to 'origin attribute') if they had not been placed there before. For instance, in the example presented in Table 9-3, the first 'attribute to assess' is 'biological hazard', since it is unknown and required. 'Biological hazard' and 'state' (from the 'List of attributes needed') are copied to 'destiny attribute' and 'origin attribute', respectively. Since 'state' is unknown, 'state' is also copied to 'destiny attribute', and consequently 'edibility' to 'origin attribute'. The process is repeated for 'edibility', which does not depend on any other attribute, and therefore receives a value n = 1.

Table 9-4. Results Table of the example presented in Table 9-3

Results Table					
n	Destiny attribute	Origin attribute			
3	Biological hazard	State			
2	State	Edibility			
1	Edibility	Ø			
4	Hazardous materials	State	Other organic compounds	Inorganic content and composition	Biological hazard
1	Other organic compounds	Ø			
1	Inorganic content and composition	Ø			
1	Total emissions to air	Distance to transport food waste	Production or flow rate		
1	CO_2, CH_4, NMVOC, PM<10	Distance to transport food waste			
1	Feeding people in need	Production or flow rate	Quantity of food redistributed		

Each time the process is repeated, the value of *n* increases by one unit. Each attribute from 'destiny attribute' receives an increasing *n* value, starting from the last attribute assessed. In the example presented, *n(edibility)* = 1, *n(state)* = 2 and *n(biological hazard)* = 3. When there are more than one attribute in 'origin attribute', the *n* value of 'destiny attribute' is the highest from all possible of 'origin attribute' + 1. For instance, it can be seen in Table 9-4 that 'hazardous materials' have an *n* = 4. The values of *n* for each of its 'origin attribute' is *n(state)* = 2, *n(other organic compounds)* = 1, *n(inorganic content and composition)* = 1 and *n(biological hazard)* = 3. Therefore, highest *n* is *n(biological hazard)* = 3 and consequently *n(hazardous materials)* = *n(biological hazard)* + 1 = 3 + 1 = 4.

The results obtained in Table 9-4 can be used to determine the attributes needed to assess unknown attributes and the order of the assessment. This has been represented in Figure 9-14, which shows known, unknown and required attributes in the different calculation steps according to their *n* value, and arrows representing information flows. The arrows must be read from top to bottom, and considering all existing intersections. The origin of the arrow represents the 'origin attribute' and the arrowhead the 'destiny attribute'.

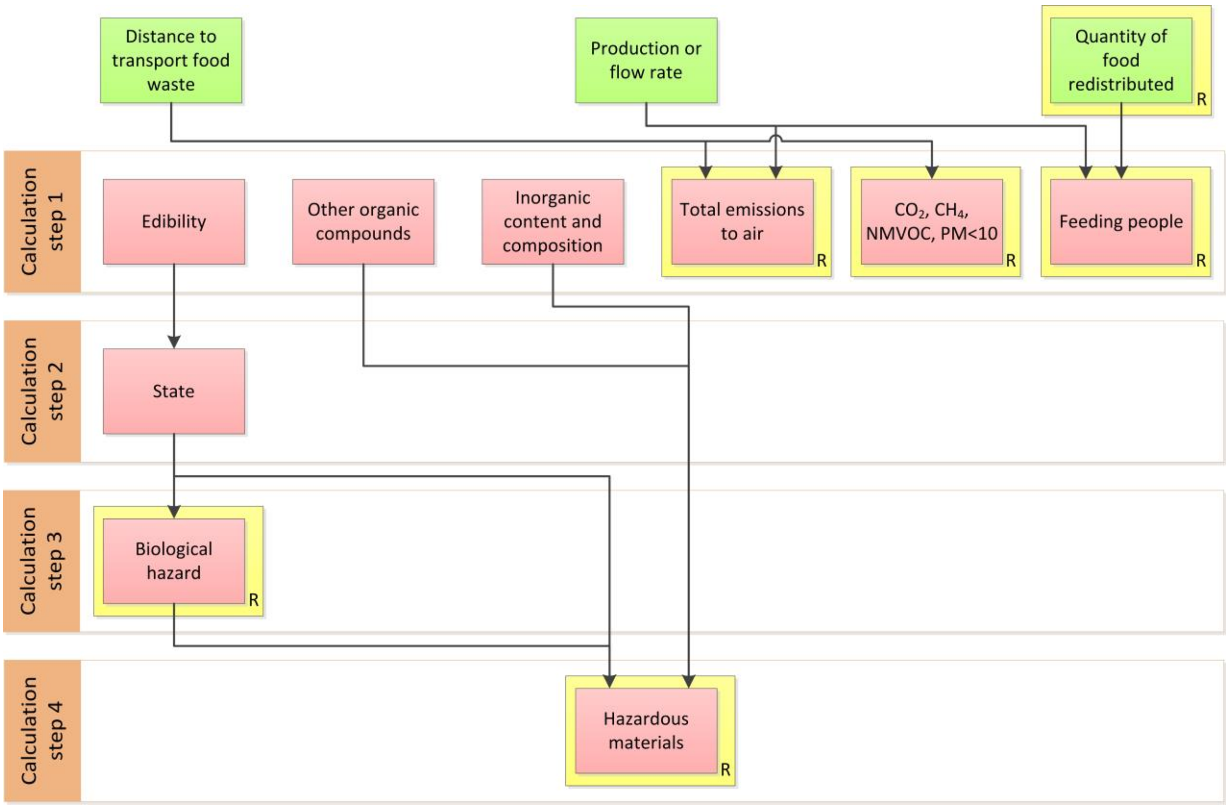


Figure 9-14. Information flow diagram built from Table 9-4. Green attributes: known attributes, red attributes: unknown attributes, attributes in yellow R boxes: required attributes

9.5 Chapter summary

This chapter has presented an analysis of the attributes presented in Sections 7.4 and 8.3 in order to identify relationships between them. The relationships identified have been collected in the Relationships Matrix, which have been simplified through a combination of attributes. A Streamlined Relationships Matrix has also been designed in order to represent only the most relevant attributes.

The Relationships Matrix has been used to create the Dependencies List, which determines which attribute depend on the other in a relationship. The Dependencies List has been used to draw information flowcharts to model redistribution for human consumption and animal feeding, and the streamlined version of the Dependencies List has been used to draw information flowcharts for anaerobic digestion, composting and thermal treatment with energy recovery. This allows identifying which attributes must be defined in order to obtain the information pursued.

The end of the chapter describes a methodology to determine the attributes needed to assess unknown attributes and the order of the assessment, integrating the research presented in Chapters 7, 8 and 9 and completing the FWM framework.

CHAPTER 10 CASE STUDIES

10.1 Introduction

In order to demonstrate and evaluate the applicability of the research presented in Chapters 7-9 and getting feedback on the use of the FWM framework, two case studies have been carried out with large UK food manufacturers: Molson Coors Brewing Co. (UK), Ltd., a subsidiary of the Molson Coors Brewing Company and referred to hereinafter as Molson Coors; and Quorn Foods, which is the trading name of Marlow Foods Limited, a manufacturer of meat alternatives. These food companies were selected because previous contact between the research group and the industries existed, and also due to their leading position in their product market, large size and therefore number of different types of FW produced. Additionally, these two companies produce two very different types of product, a drink and a solid food, and therefore the applicability of the research could be evaluated against these diverse products.

Three main approaches were used to collect data: site visits, interviews and questionnaires. Before the site visits both telephone and email contact were used to identify interests of the companies participating in the study, present the methodology of the FW analysis and explain the main objectives of the case studies. Following initial contact, site visits to the respective companies' headquarters took place to gain a better understanding of the FW generated. In-person interviews were held with company employees: the Product and Process Development Brewer of Molson Coors and the Environment & Sustainability Manager of Quorn Foods. During the interviews, a questionnaire was used to systematically identify FW streams and collect relevant qualitative and quantitative data. An example of the questionnaire used is shown in Appendix 1. The questionnaire was filled for each FW identified in each food company, according to the FW definition and delimitation of the boundaries of the food system explained in Section 7.2. Following the site visits and in-person interviews, further email contact was needed to collect additional information. Consultation with other company employees was also necessary to collect all necessary data (e.g. from production and purchasing departments).

The data presented in this chapter are original data provided by the food manufacturers, as well as published data on the types of FW identified (e.g. edibility of different materials and relevant legislation). Sensible assumptions have been made where suitable information was not available with regard to decide which attributes are known or unknown (Sections 10.2.2 and 0) and the type of diatomaceous earth used (Section 10.2.1.4). It should be noted that some of the data collected and generated is not reported here because of confidentiality agreements with the food companies involved (e.g. economic performance of FWM).

This chapter is divided into two main sections, one for each case study. Each section begins by giving an overview of the food company, and then describes the FW types identified according to the definition of FW provided in Section 7.2.1 and the boundaries delimited in Section 7.2.2. Each FW has been categorised following the nine-stage categorisation presented in Section 7.4 and its most sustainable FWMS has been found by using the FWMDT from Section 7.5. The FW types that could be managed in a more sustainable way have been further assessed by using the FWMMP presented in Chapter 8, and finally the research ideas presented in Sections 9.3 and 9.4 have been used to generate information flow diagrams to support the estimation of results generated from the proposed FWMS.

10.2 Brewery: Molson Coors

Molson Coors is a multinational brewing company that produces beer brands such as Carling, Coors Light and Cobra Beer. The headquarters of its UK arm, located in Burton upon Trent in Staffordshire, produces 652,000,000 litres of beer per year. Beer is manufactured through a number of process stages: malting the raw material (mostly barley, but other materials such as wheat can also be added to the initial mixture), milling, mashing with water, mixing with hops and brewing in kettles, separation of sediments, fermentation, maturation, filtration, pasteurisation and packaging.

Beer production in Molson Coors generates approximately the same quantity of wet FW than that of final product, i.e. proportion *product/FW* = 1:1, although if dried the FW volume is reduced to one third, i.e. proportion *product/FW* = 3:1. Most of the dried FW corresponds to barley used in the mashing process, with a small quantity of wheat and sugar. The quantity of total FW generated is directly linked to the level of production, e.g. in August the amount of FW is twice as big as in February because the demand is double in the hot season. It is estimated that liquid waste amounts to approximately 7% of the total beer production. In the beginning of the production line liquid waste is water with a small concentration of other substances, and near the end of the line the liquid waste is more similar to beer in composition. The remainder waste is either solid or wet waste. This section only assesses solid/wet FW and final product waste (waste beer).

10.2.1 Identification and categorisation of FWs, and selection of a FWMS

This section identifies and categorises the different types of FW generated at Molson Coors' manufacturing plant located in Burton upon Trent, according to the definition of FW provided in Section 7.2.1 and the boundaries delimited in Section 7.2.2. The different types of FW identified, in order of decreasing quantity, are spent grain, waste beer, conditioning bottom, filter waste and trub. It must be noted that Molson Coors also generates 10,000 – 11,000 t/year of a by-product from the mashing process, namely spent yeast. This is currently sold to Unilever, also located in Burton upon Trent, to produce Marmite®, a food spread. This by-product is not considered FW according to the definition provided in Section 7.2.1, and therefore is out of the scope of this work, because it is sold as planned by Molson Coors and used to produce a food product. If spent yeast were sent for any other use, it would be considered FW and its assessment would be necessary.

The FWs identified are assessed in the following sub-sections. Possible alternative options from the FWH are suggested as further possibilities when their sustainability performance has been estimated to be higher than that of the suggested alternative. For instance, the suggested FWMS for conditioning bottom cannot be redistribution for human consumption because the FW is unprocessed; nevertheless the potential to use this food material to produce new food products has been assessed. Similarly, some industrial uses are out of the scope of the FWMDT, but they have been assessed independently.

In the following tables, 'N/A' means not applicable, e.g. 'packaging biodegradability' cannot be assessed for unpackaged FW. 'N/N' means that the information is not necessary, e.g. for spent grain, 'treatment' is not needed, since inedible, plant-based, single product can be treated indifferently whether the FW is processed or not (see Figure 7-10). The current treatment has been highlighted in green when the proposed FWMS coincides with the current treatment and in red when a more sustainable solution has been found.

10.2.1.1 Spent grain

Spent grain represents around 85% of the total FW in the manufacturing plant. It is an unavoidable by-product discarded after the mashing process and is composed of barley and small amounts of wheat.

According to the point in the production line where this FW is generated (Section 7.3), spent grain can be considered a by-product from an incomplete food (the mashing mixture).

Table 10-1 classifies spent grain according to the nine-stage categorisation presented in Section 7.4. Additionally, the most sustainable FWMS was identified by using the FWMDT (Section 7.5): animal feeding.

Currently, spent grain is mixed with trub and used for animal feeding, which is the FWMS selected using the FWMDT. The mixture has an approximate proportion of 99% spent grain, 1% trub.

The possibility of reprocessing the spent grain to adapt it for human consumption has also been explored to assess the potential to upgrade this FW. If spent grain is processed for human consumption, it must not be mixed with trub and must be managed separately. Spent grain contains a high proportion of dietary fibres and proteins which may provide a number of health benefits (Santos et al. 2003). It can be used to produce flour through a process that includes drying and grinding (Santos et al. 2003). This can be mixed afterwards with wheat flour and used in a wide range of food products to increase their health benefits, e.g. bread,

Table 10-1. Categorisation of spent grain and identification of its most sustainable FWMS

Spent grain	
Unavoidable by-product from incomplete food	
Edibility	Inedible
State	N/A
Origin	Plant based
Complexity	Single product
Animal-product presence	N/A
Treatment	N/N
Packaging	N/N
Packaging biodegradability	N/N
Stage of the supply chain	Non-catering waste
Current treatment	Animal feeding
Proposed FWMS	Animal feeding
Other possibilities	Production of foodstuff
Quantity	≈ 70,000 t/year

muffins or biscuits (Mussatto et al. 2006). It must be noted that production of new food products was not selected by using the FWMDT because spent grain was considered inedible, since currently there is no consumer demand for the aforementioned products or economically advantageous technologies to produce them. In case that technology existed to produce new food products from spent grain, such as those described above, and these food products could be sold because there was a consumer demand for it, spent grain would not be considered FW providing it was used for this purpose.

Other uses for spent grain, apart from food uses and for animal feeding, include pet food, use in construction bricks, removal of pollutants in wastewater, production of paper, growing medium for mushrooms or microorganisms, extraction and synthesis of compounds (e.g. bioethanol, lactic acid, polymers and resins, hydroxycinnamic acids, arabinooligoxylosides, xylitol, pullulan), anaerobic digestion, composting, thermal treatment with energy recovery and landspreading (Mussatto et al. 2006, Environmental Protection Agency 2008, Aliyu & Bala 2013).

10.2.1.2 Waste beer

Waste beer is the final product but which is not ultimately consumed. There are three reasons as to why this FW is generated:

1. Beer left in casks brought back from the food service sector. This represents most of the FW in this category. It causes an economic loss to the food service sector, not to the brewing company. Therefore, it has not been given a significant importance by the brewery.
2. Beer rejected because of mislabelling.
3. Spilled beer in the filling process. This accounts for a negligible amount.

According to the point in the production line where this FW is generated (Section 7.3), waste beer can be considered the final food product (beer left in casks and mislabelled beer) or processed food (spilled beer).

Table 10-2 classifies waste beer according to the nine-stage categorisation presented in Section 7.4. Unsurprisingly, the most sustainable FWMS is identified using the FWMDT (Section 7.5): redistribution for human consumption.

Table 10-2. Categorisation of waste beer and identification of its most sustainable FWMS

Waste beer	
Final food product or processed food	
Edibility	Edible
State	Eatable
Origin	Plant based
Complexity	Single product
Animal-product presence	N/A
Treatment	Processed
Packaging	Separable from packaging
Packaging biodegradability	N/N
Stage of the supply chain	Non-catering waste
Current treatment	95% animal feeding + 5% sewage
Proposed FWMS	Redistribution for human consumption
Other possibilities	N/N
Quantity	14,000 t/year

Currently, 95% of the waste beer is sent to farms and mixed with other waste to feed pigs. The remaining 5% is sent to sewage.

Ideally, and according to the FWMDT (Figure 7-8), beer left in casks could be reused for human consumption; nevertheless, since this FW comes from outside of the factory, it is difficult to prove that it has not been altered and is still safe for human consumption, i.e. that it is still 'eatable'. Should waste beer be considered safe for consumption but of low quality, ethical issues may also arise regarding the benefits of using it for human consumption. If the option of redistribution for human consumption is discarded, the next recommended alternative is animal feeding, which is the current final use.

Beer rejected because of mislabelling is perfectly potable, so it is potentially reusable. Nevertheless, extracting the product from its packaging (i.e. emptying bottles and dispensing the product into new bottles) or amending the packaging is difficult and resource consuming, since this would require significant employee time or new technologies for process automation. Otherwise, mislabelled beer can be sold in England to a redistributor of surplus products such as the Company Shop at a lower price, where the label is corrected to meet Food Information Regulations 2014 (Statutory Instruments 2014). Providing the beer is compliant with food safety legislation, it can be sold at a lower price to the final consumer as well, and therefore, this material would not be considered FW any longer. European legislation that regulates the food information that must be provided to consumers in product labelling is the Regulation (EU) No 1169/2011 (The European Parliament and the Council of the European Union 2011). Food banks generally do not serve beer and therefore it may not be possible to redistribute this product to charities for human consumption. Nevertheless, it can still be possible to use this beer in some charitable activities, such as fundraising or raising-awareness events, considering management of liability.

Alternatively, distillation to extract alcohol can be carried out in all types of waste beer, providing an economic income. A distiller's licence, approval for the plant and process and to account for and pay Spirits Duty to HM Revenue and Customs is required to distil alcoholic liquids in the UK (Gov.uk 2016).

10.2.1.3 Conditioning bottom

Conditioning bottom is an unavoidable by-product which sediments to the bottom of the conditioner tanks during the maturation process and is removed after the process is finished. It is composed principally of yeast, which is an edible material. However, it is not suitable for redistribution for human consumption, because conditioning bottom is unprocessed.

According to the point in the production line where this FW is generated (Section 7.3), conditioning bottom can be considered an unavoidable by-product from an unprocessed food (the conditioned beer). Conditioned beer is considered unprocessed because it still has to undergo the pasteurisation process.

Table 10-3 classifies conditioning bottom according to the nine-stage categorisation presented in Section 7.4.

The most sustainable FWMS identified using the FWMDT (Section 7.5) is animal feeding. It must be noted that the 'microorganisms' attribute, from 'origin', was considered as plant based, since it is not under animal by-product regulations. Currently, conditioning bottom is used to feed pigs, which is the optimal alternative according to the FWMDT (Figure 7-8).

Alternatively, some substances from the conditioning bottom can be used to produce new food products. Yeast can be separated and used to produce food for human consumption. In this case, the sediment should be filtered and compressed, giving the opportunity to recover cloudy-type beer. As well as with spent grain, production of new food products was not selected by using the FWMDT because conditioning bottom is unprocessed, since there is

Table 10-3. Categorisation of conditioning bottom and identification of its most sustainable FWMS

Conditioning bottom	
Unavoidable by-product from unprocessed food	
Edibility	Edible
State	Eatable
Origin	Principally microorganisms
Complexity	Single product
Animal-product presence	N/A
Treatment	Unprocessed
Packaging	Unpackaged
Packaging biodegradability	N/A
Stage of the supply chain	Non-catering waste
Current treatment	Animal feeding
Proposed FWMS	Animal feeding
Other possibilities	Production of foodstuff
Quantity	7000 t/year

no current consumer demand for it or no technology available to undertake the processes required.

10.2.1.4 Filter waste

Filter waste is composed of diatomaceous earth, yeast and proteins. Yeast and proteins are edible materials. Diatomaceous earths are fossilized remains of diatoms, and although they are typically considered inedible, there are two types of this material: food grade diatomaceous earth and inedible diatomaceous earth. In order to choose the best FWMS the type of diatomaceous earth must first be identified. Since the current use for beer production is as a filter medium, it has been assumed that the diatomaceous earth was inedible.

According to the point in the production line where this FW is generated (Section 7.3), filter waste can be considered an unavoidable by-product from an unprocessed food (the conditioned beer).

Table 10-4 classifies filter waste according to the nine-stage categorisation presented in Section 7.4. Consequently, the most sustainable FWMS is identified using the FWMDT

(Section 7.5): anaerobic digestion. It must be noted that the 'microorganisms' attribute, from 'origin', was considered as plant based, since it is not under animal by-product regulations.

Following the FWMDT (Figure 7-10), this FW should be used for animal feeding. However, the type of diatomaceous earth used has been assumed to be not suitable for animal feeding and therefore the next alternative from the FWH has been suggested: anaerobic digestion. Currently, there are two types of filter waste: dry waste, which is sent to composting, and wet waste, which is sent to sewage. Both solutions are less sustainable than the proposed FWMS.

Potential additional uses of diatomaceous earth include industrial applications, such as filter medium, stabiliser of nitroglycerin, abrasive in metal polishes and toothpaste, thermal insulator, reinforcing filler in plastics and rubber, anti-block in plastic films, support for catalysts, activation in blood coagulating studies and cat litter. Other uses include additive in ceramic mass for the production of red bricks, insecticide and anticaking agent for grain storage (when it is food grade), growing medium in hydroponic gardens and plotted plants and landspreading (Ferraz et al. 2011, Anon n.d.).

Table 10-4. Categorisation of filter waste and identification of its most sustainable FWMS

Filter waste	
Unavoidable by-product from unprocessed food	
Edibility	Inedible
State	N/A
Origin	Microorganisms
Complexity	Mixed product
Animal-product presence	Not in contact with or containing animal-based products
Treatment	N/N
Packaging	N/N
Packaging biodegradability	N/N
Stage of the supply chain	Non-catering waste
Current treatment	50 % compost + 50 % sewage
Proposed FWMS	Anaerobic digestion
Other possibilities	Industrial uses
Quantity	1200 t/year

10.2.1.5 Trub

Trub is an unavoidable by-product obtained in the separator after the brewing process. It is composed of hops, inactive yeast, heavy fats and proteins.

According to the point in the production line where this FW is generated (Section 7.3), trub can be considered a by-product from an incomplete food (the post-brewing wort).

Table 10-5 classifies trub waste according to the nine-stage categorisation presented in Section 7.4. Additionally, the most sustainable FWMS is identified using the FWMDT (Section 7.5): animal feeding.

Currently, trub is mixed with spent grain and sent to animal feeding, which is the best FWMS according to the FWMDT (Figure 7-10).

On the other hand, whilst hops are typically considered inedible, some parts are actually edible. For example, hop shoots can be consumed by humans (The Guardian 2015). Edible parts of the hops can be separated and used in new food products, with the remaining hops

Table 10-5. Categorisation of trub waste and identification of its most sustainable FWMS

Trub waste	
Unavoidable by-product from incomplete food	
Edibility	Inedible
State	N/A
Origin	Plant based
Complexity	Mixed product
Animal-product presence	Not in contact with or containing animal-based products
Treatment	N/N
Packaging	N/N
Packaging biodegradability	N/N
Stage of the supply chain	Non-catering waste
Current treatment	Animal feeding
Proposed FWMS	Animal feeding
Other possibilities	Production of foodstuff
Quantity	≈ 700 t/year

being sent to animal feeding. Yeast, fats and proteins can also be potentially used in new food products. As well as with spent grain, production of new food products was not selected by using the FWMDT because trub was considered inedible, as there is no current consumer demand for the aforementioned products or no technology available to undertake the processes required. In case that technology existed to produce new food products from trub, such as those described above, and these food products could be sold because there was a consumer demand for it, trub would not be considered FW providing it was used for this purpose.

10.2.2 Analysis of information flows

This section applies the research ideas presented in Sections 9.3 and 9.4 to the two types of upgradeable Molson Coors' FW identified in Section 10.2.1: waste beer and filter waste, for which redistribution for human consumption and anaerobic digestion are the FWMSs proposed respectively. As a result, Tables of Assessment have been completed for each FW and Results Tables have been generated. Finally, the Results Tables have been used to depict optimal information flows which can be seen in information flow diagrams. This allows an easier estimation of outputs and implications generated from the FWMSs proposed based on available information.

10.2.2.1 Waste beer

The attributes needed to model redistribution for human consumption, according to Chapter 8, are listed in the Table of Assessment (Table 10-6). The classification of attributes as known/unknown and required/non-required has been decided based on conversations with staff from Molson Coors and reasonable assumptions if any information was not available. Consequently, the following attributes have been classified as unknown:

- 'State', 'biological hazard' and 'hazardous materials', because these parameters are unknown for beer left in casks brought back from the food service sector, since beer could have been altered.
- All performance factors and sustainability indicators, because redistribution for human consumption has not yet been used for waste beer and therefore the results generated from this FWMS are still unknown.

Table 10-6. Table of Assessment for waste beer

Category of attribute to assess	Attribute to assess	Is the value of the attribute known?	Mark the attributes required	List of attributes needed									Known dependencies	Unknown dependencies
Qualitative food-waste parameters	Edibility	Y												
	State	N		Edibility									1	
	Treatment	Y												
Primary quantitative food-waste parameters	Production or flow rate	Y	R											
	Biological hazard	N		State										1
	Other organic compounds	Y												
	Inorganic content and composition	Y												
Secondary quantitative food-waste parameters	Hazardous materials	N		State	Other organic compounds	Inorganic content and composition	Biological hazard						2	2
	Density	Y												
Process and company variables	Distance to transport food waste	Y		Production or flow rate									1	
Performance factors	Quantity of food redistributed	N	R	Edibility	Treatment	Distance to transport food waste	State	Hazardous materials	Production or flow rate	Biological hazard	Inorganic content and composition	Other organic compounds	6	3
Environmental indicators: impacts to air	Total emissions to air	N	R	Distance to transport food waste	Production or flow rate								2	
	CO_2, CH_4, NMVOC, PM<10	N	R	Distance to transport food waste									1	
	N_2O, NOx	N	R	Distance to transport food waste									1	
	Total organic carbon (TOC), dust, PM<2.5	N	R	Distance to transport food waste									1	
Environmental indicators: impacts to water														
Environmental indicators: impacts to soil														
Economic indicators	Management cost	N	R	Production or flow rate	Distance to transport food waste	Quantity of food redistributed							2	1
Social indicators	Support of local economies	N		Production or flow rate	Quantity of food redistributed								1	1
	Job creation	N		Production or flow rate	Quantity of food redistributed								1	1
	Noise	N		Production or flow rate	Quantity of food redistributed	Distance to transport food waste							2	1
	Feeding people	N	R	Production or flow rate	Quantity of food redistributed								1	1
	Traffic	N		Production or flow rate	Quantity of food redistributed	Density	Distance to transport food waste						3	1
												Total	25	12

Known attributes are those referring to general characteristics of beer and its manufacturing (e.g. 'edibility', 'density' and 'treatment'), quantity of waste beer generated (14,000 t/year) and distance to transport it. Required attributes are related to the quantity of waste beer available to redistribute, environmental impacts to air, 'management cost' as economic indicator and 'feeding people' as social indicator. The Table of Assessment shows which attributes are needed to assess each attribute (i.e. 'List of attributes needed') and the number of known and unknown attributes for each attribute to assess.

Once the Table of Assessment has been completed, a Results Table can be prepared by using the methodology explained in Section 9.4. The Results Table for waste beer (Table 10-7) shows the order (*n*) in which each attribute must be assessed, and the attributes needed for that assessment ('origin attribute').

Finally, the Results Table has been used to draw an information flow diagram (Figure 10-1) that represents the order of assessment for each attribute and the attributes needed for each assessment. The arrows must be read from top to bottom, and considering all existing intersections. It can be seen that for redistribution for human consumption of waste beer, five calculation steps are needed in order to estimate all required attributes. 'Edibility', 'production or flow rate', 'distance to transport food waste', 'other organic compounds', 'inorganic content' and 'composition and treatment' should be used to assess the required attributes: 'total emissions to air', 'CO_2, CH_4, NMVOC, PM<10', 'N_2O, NOx', 'TOC, dust, PM<2.5', 'quantity of food redistributed', 'management cost' and 'feeding people'. 'State',

Table 10-7. Results Table for waste beer

n	Destiny attribute			
4	Quantity of food redistributed	Edibility	Treatment	Distance to transport food waste
1	State	Edibility		
3	Hazardous materials	State	Other organic compounds	Inorganic content and composition
2	Biological hazard	State		
1	Total emissions to air	Distance to transport food waste	Production or flow rate	
1	CO_2, CH_4, NMVOC, PM<10	Distance to transport food waste		
1	N_2O, NOx	Distance to transport food waste		
1	TOC, dust, PM<2.5	Distance to transport food waste		
5	Management cost	Production or flow rate	Distance to transport food waste	Quantity of food redistributed
5	Feeding people	Production or flow rate	Quantity of food redistributed	

Results Table

Origin attribute					
State	Hazardous materials	Production or flow rate	Biological hazard	Inorganic content and composition	Other organic compounds
Biological hazard					

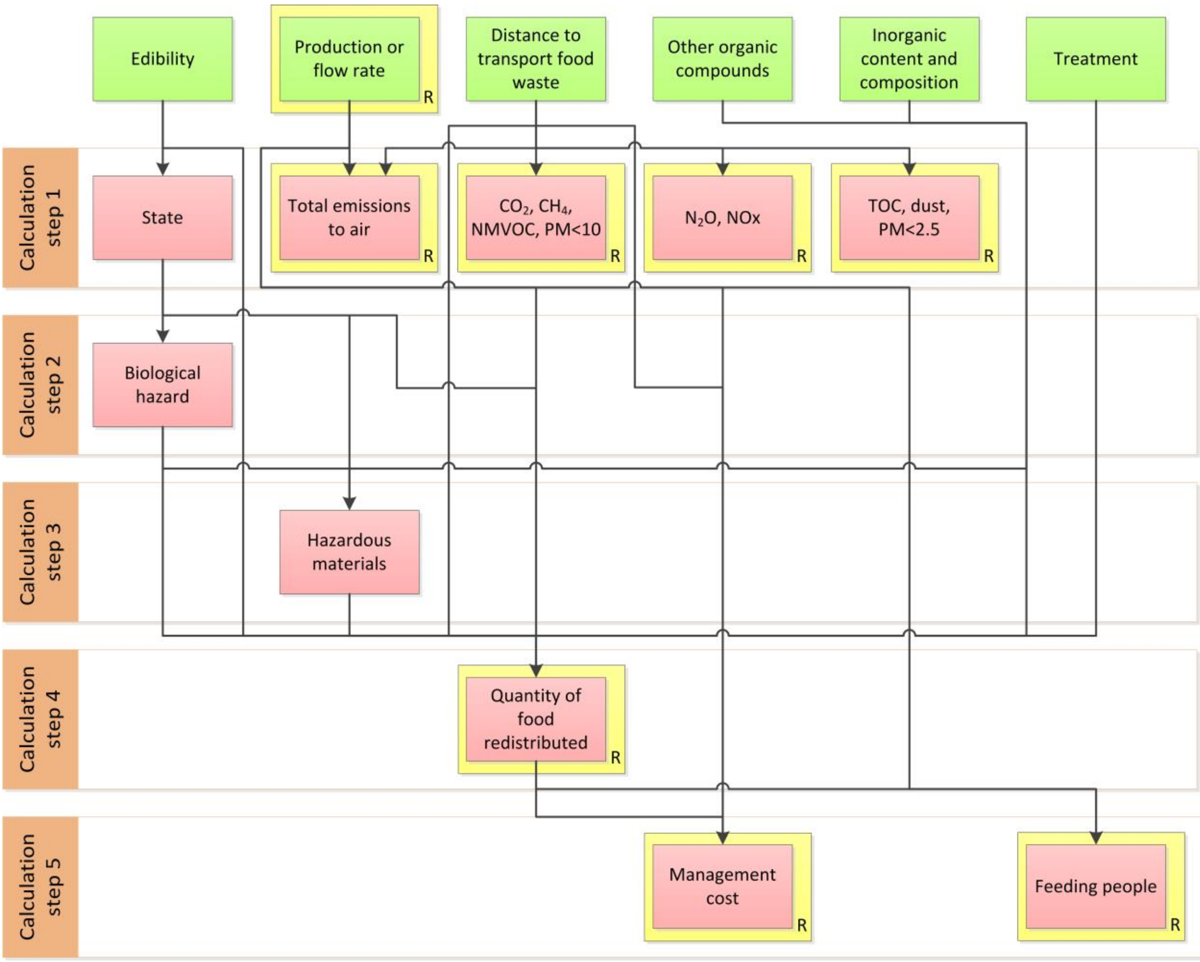


Figure 10-1. Information flow diagram for waste beer

'biological hazard' and 'hazardous materials' are unknown attributes which must also be evaluated to be able to assess the required attributes.

10.2.2.2 Filter waste

The attributes needed to model anaerobic digestion, according to Chapter 8, are listed in the Table of Assessment (Table 10-8). The classification of attributes as known/unknown and required/non-required has been decided based on conversations with staff from Molson Coors and reasonable assumptions if any information was not available. Consequently, the attributes classified as unknown are secondary quantitative FW parameters ('volatile solids', 'total solids' and 'C:H:O:N:P:S ratio'), 'organic loading rate', and all performance factors and sustainability indicators, because anaerobic digestion has not been used yet to treat filter waste and therefore the results generated from this FWMS are still unknown. Known attributes are those referring to general characteristics of the filter waste and its

Table 10-8. Section of Table of Assessment for filter waste showing categories of attributes, attributes to asses, known/unknown attributes, and required attributes

Category of attribute to assess	Attribute to assess	Is the value of the attribute known?	Mark the attributes required
Qualitative food-waste parameters	Origin	Y	
	Complexity	Y	
	Animal-material presence	Y	
	Packaging	Y	
	Packaging biodegradability	Y	
Primary quantitative food-waste parameters	Production or flow rate	Y	
	Carbohydrate content and composition	Y	
	Fat content and composition	Y	
	Protein content and composition	Y	
	Vitamin content and composition	Y	
	Other organic compounds	Y	
	Inorganic content and composition	Y	
	Moisture content	Y	
	Biological hazard	Y	
	pH (FW parameter)	Y	
	Particle size	Y	
Secondary quantitative food-waste parameters	Density	Y	
	Hazardous materials	Y	
	Volatile solids (VS)	N	
	Total solids (TS)	N	
	C:H:O:N:P:S ratio	N	
Process and company variables	Distance to transport food waste	Y	
	Volume of equipment available	Y	
	Temperature	Y	
	Process time	Y	
	pH (process variable)	Y	
	Organic loading rate (OLR)	N	
Performance factors	Biogas production rate	N	
	[CH4] in biogas	N	
	Digestate flow rate	N	
	Digestate composition	N	
Environmental indicators: impacts to air	Total emissions to air	N	
	CO_2, CH_4	N	
Environmental indicators: impacts to water	Wastewater flow	N	
	COD, TSS	N	
Environmental indicators: impacts to soil	Solid residue flow rate	N	
	Nutrient content: N	N	
	Nutrient content: P	N	
	Nutrient content: K	N	
Economic indicators	Management cost	N	R
	Economic value of solid material	N	R
	Heat recovered / Output power	N	R
	Biogas rate	N	
	[CH4] in biogas	N	
Social indicators	Support of local economies	N	
	Job creation	N	
	Noise	N	
	NIMBY syndrome	N	
	Traffic	N	

manufacturing (the remaining FW parameters and process and company variables). Required attributes in order to decide on whether to use anaerobic digestion are related to the economic performance of the FWMS: 'management cost', 'economic value of solid material' (i.e. digestate) and 'heat recovered / output power'. The Table of Assessment informs of which attributes are needed to assess each attribute (i.e. 'List of attributes needed') and the number of known and unknown attributes for each attribute to assess, nevertheless in Table 10-8 this specific information has been excluded due to size limitations.

Once the Table of Assessment has been completed, a Results Table can be prepared by using the methodology explained in Section 9.4. The Results Table for filter waste (

Table 10-9) shows the order (*n*) in which each attribute must be assessed, and the attributes needed for that assessment ('origin attribute').

Finally, the Results Table has been used to draw an information flow diagram (Figure 10-2) that represents the order of assessment for each attribute and the attributes needed for each assessment. It can be seen that for anaerobic digestion of filter waste, four calculation steps are needed in order to estimate all required attributes.

10.2.3 Discussion and conclusions of the research applied to Molson Coors

The nine-stage categorisation and FWMDT (Chapter 7) have been proved to be useful to analyse Molson Coors' FW, since two types of FW (waste beer and filter waste) have been identified to be suitable to be managed in a more sustainable way.

The assessment of some categories was complex for some FWs, e.g. 'edibility' for spent grain and 'state' for waste beer. Spent grain was demonstrated to be an edible material, although there is no market for it for human consumption, and thus spent grain waste was consequently classified as inedible. Research and investment to produce new food products from spent grain is encouraged, and when that is achieved the categorisation of spent grain would need amendment. Waste beer was classified as eatable, however safety concerns regarding beer left in casks brought back from the food service sector must be overcome before the beer is reused.

The feasibility of sending FW to animal feeding was also difficult to determine. It was found that when considering animal feeding for inedible, plant-based, single or mixed product not in contact with or containing animal-based products, non-catering FW (Figure 7-10) each type of FW should be assessed independently. For instance, whilst trub can be sent for animal feeding, filter waste cannot be used for that purpose since it contains diatomaceous earth which was assumed to be indigestible by animals.

FW principally composed of yeast cannot be strictly classified as plant-based or animal-based. The 'microorganisms' parameter was introduced for this reason, but in practice this material was considered as plant-based, since it is not under animal by-product regulations.

Table 10-9. Results Table for filter waste

Results Table

n	Destiny attribute	Origin attribute	
4	Management cost	Production or flow rate	Biological hazard
2	Organic loading rate (OLR)	Production or flow rate	Carbohydrate content and composition
1	Volatile solids (VS)	Carbohydrate content and composition	Fat content and composition
1	Total solids (TS)	Carbohydrate content and composition	Fat content and composition
1	C:H:O:N:P:S ratio	Carbohydrate content and composition	Fat content and composition
3	Biogas production rate	Packaging biodegradability	Production or flow rate
3	Digestate flow rate	Packaging biodegradability	Production or flow rate
4	Economic value of solid material	Biological hazard	Hazardous materials
3	Digestate composition	Packaging biodegradability	Carbohydrate content and composition
4	Heat recovered / Output power	Biogas production rate	[CH4] in biogas
3	[CH4] in biogas	Packaging biodegradability	Carbohydrate content and composition

n	Destiny attribute	Origin attribute (cont.)			
4	Management cost	Hazardous materials	Distance to transport food waste	Volume of equipment available	Temperature
2	Organic loading rate (OLR)	Fat content and composition	Protein content and composition	Vitamin content and composition	Other organic compounds
1	Volatile solids (VS)	Protein content and composition	Vitamin content and composition	Other organic compounds	Inorganic content and composition
1	Total solids (TS)	Protein content and composition	Vitamin content and composition	Other organic compounds	Inorganic content and composition
1	C:H:O:N:P:S ratio	Protein content and composition	Vitamin content and composition	Other organic compounds	Inorganic content and composition
3	Biogas production rate	Carbohydrate content and composition	Fat content and composition	Protein content and composition	Vitamin content and composition
3	Digestate flow rate	Carbohydrate content and composition	Fat content and composition	Protein content and composition	Vitamin content and composition
4	Economic value of solid material	Digestate composition			
3	Digestate composition	Fat content and composition	Protein content and composition	Vitamin content and composition	Other organic compounds
4	Heat recovered / Output power				
3	[CH4] in biogas	Fat content and composition	Protein content and composition	Vitamin content and composition	Other organic compounds

n	Destiny attribute	Origin attribute (cont.)				
4	Management cost	Process time	pH (process variable)	Organic loading rate (OLR)	Biogas production rate	Digestate flow rate
2	Organic loading rate (OLR)	Inorganic content and composition	Moisture content	Biological hazard	Particle size	Density
1	Volatile solids (VS)					
1	Total solids (TS)	Moisture content				
1	C:H:O:N:P:S ratio	Moisture content	Biological hazard	Hazardous materials		
3	Biogas production rate	Other organic compounds	Inorganic content and composition	Moisture content	Biological hazard	pH (FW parameter
3	Digestate flow rate	Other organic compounds	Inorganic content and composition	Moisture content	Biological hazard	pH (FW parameter
4	Economic value of solid material					
3	Digestate composition	Inorganic content and composition	Moisture content	Biological hazard	pH (FW parameter)	Particle size
4	Heat recovered / Output power					
3	[CH4] in biogas	Inorganic content and composition	Moisture content	Biological hazard	pH (FW parameter)	Particle size

n	Destiny attribute	Origin attribute (cont.)				
4	Management cost					
2	Organic loading rate (OLR)	Volatile solids (VS)	Total solids (TS)	C:H:O:N:P:S ratio	Volume of equipment available	Temperature
1	Volatile solids (VS)					
1	Total solids (TS)					
1	C:H:O:N:P:S ratio					
3	Biogas production rate	Particle size	Density	Hazardous materials	Volatile solids (VS)	C:H:O:N:P:S ratio
3	Digestate flow rate	Particle size	Density	Hazardous materials	Total solids (TS)	C:H:O:N:P:S ratio
4	Economic value of solid material					
3	Digestate composition	Density	Hazardous materials	Total solids (TS)	C:H:O:N:P:S ratio	Temperature
4	Heat recovered / Output power					
3	[CH4] in biogas	Density	Hazardous materials	Volatile solids (VS)	C:H:O:N:P:S ratio	Temperature

n	Destiny attribute	Origin attribute (cont.)				
4	Management cost					
2	Organic loading rate (OLR)	Process time	pH (process variable)			
1	Volatile solids (VS)					
1	Total solids (TS)					
1	C:H:O:N:P:S ratio					
3	Biogas production rate	Volume of equipment available	Temperature	Process time	pH (process variable)	Organic loading rate (OLR)
3	Digestate flow rate	Volume of equipment available	Temperature	Process time	pH (process variable)	Organic loading rate (OLR)
4	Economic value of solid material					
3	Digestate composition	Process time	pH (process variable)	Organic loading rate (OLR)		
4	Heat recovered / Output power					
3	[CH4] in biogas	Process time	pH (process variable)	Organic loading rate (OLR)		

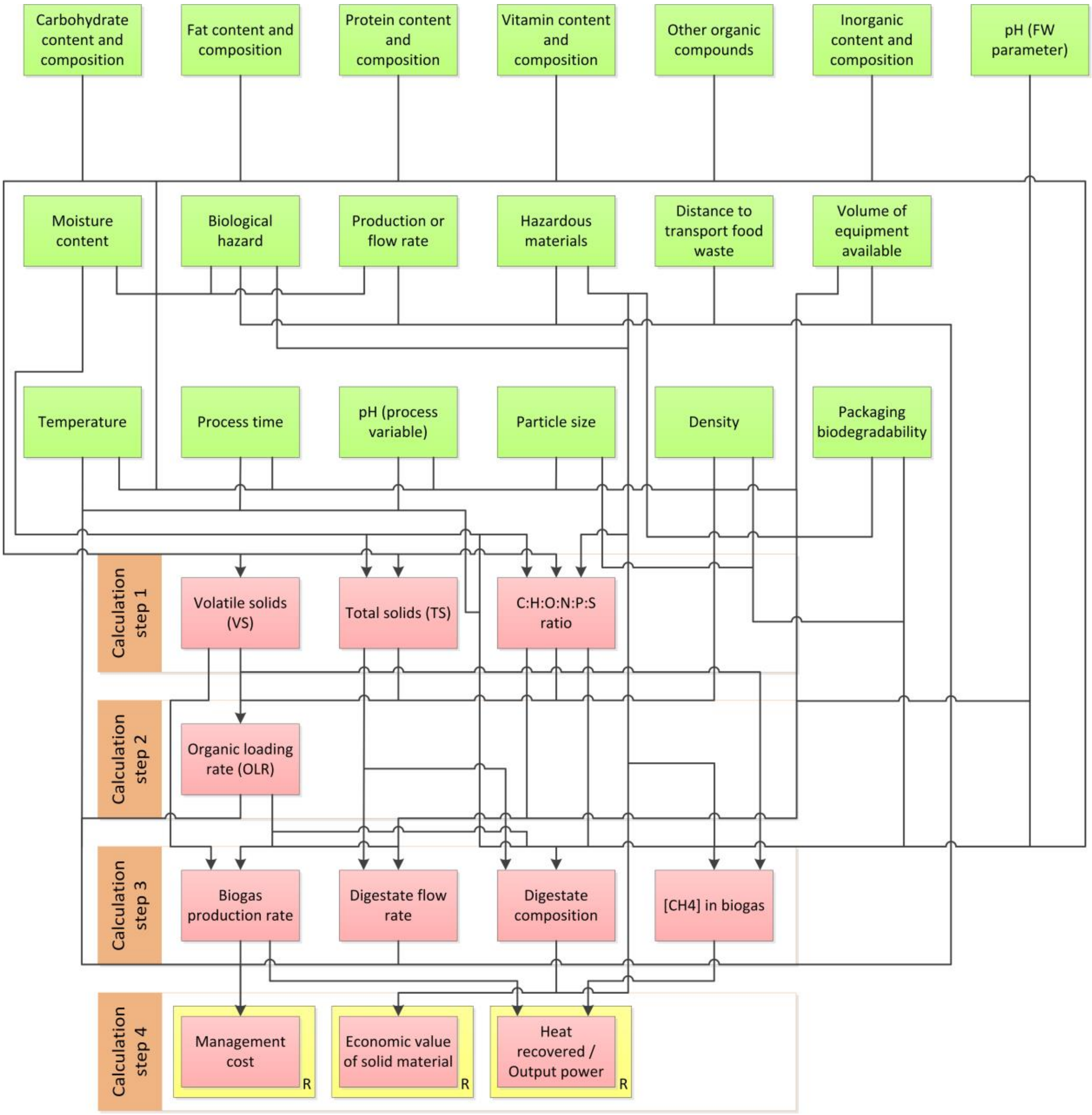


Figure 10-2. Information flow diagram for filter waste

In addition to the FWMSs from the FWMDT, industrial uses and extraction of compounds of interest were considered as alternative FWMSs for spent grain and filter waste, as suggested in Section 7.5.1.6.

The systematic analysis carried out with Molson Coors' FW is also useful to identify the most beneficial strategy for the company in order to improve their FWM. The most significant FW is the spent grain removed after the mashing process, which accounts for about 85% of the total FW generated at the plant. Although theoretically it is already managed in the most sustainable way, a long-term plan to produce new food products from spent grain could give an economic income significantly higher than that currently obtained selling it for animal feeding, converting a currently inedible FW in an edible FW. With regard to the two FWs identified as upgradeable (i.e. waste beer and filter waste), it can be concluded that improvements in waste beer management must be prioritised in the short term because of the following reasons:

1. Current waste beer management entails a higher economic cost than filter waste management.
2. Waste beer is generated in higher quantities than filter waste.
3. Since waste beer has completed all the manufacturing processes, from a life-cycle approach waste beer has associated a higher use of resources compared to filter waste, which means a higher environmental impact and loss of economic resources.

From the three types of waste beer generated, the easiest to improve its management is beer rejected because of mislabelling. Preferably, improvements in technology and management practices should be used to reduce this FW, secondly an investment in machinery and/or workforce would allow for a reuse of the beer in new bottles or the amendment of bottles labels, thirdly mislabelled beer should be sold to a redistributor of surplus products at a lower price, and last it should be sent to charities for philanthropic purposes. From these four options, the former two are considered prevention of FW, thus they were not considered in the analysis with the FWMDT.

The two FWs identified as upgradeable (i.e. waste beer and filter waste) have been further analysed in order to support an estimation of the outputs and implications of the proposed FWMSs. A combination of known/unknown and required/non-required attributes has been used to generate information flow diagrams for both FW types. Consequently, all calculation steps necessary to estimate results generated from the proposed FWMSs have been identified.

For redistributed waste beer, six known attributes were shown to be needed to assess seven required attributes, although three additional unknown attributes were also needed to be assessed to complete the assessment process. Similarly, for filter waste sent for anaerobic digestion, nineteen known attributes were shown to be needed to assess eight unknown attributes, and these twenty-seven attributes were proposed to assess the three required attributes. Nevertheless, some extra information not included in the FWMMP might be needed to complete the assessment process in some circumstances. This is a limitation of the FWM framework, and consequently the identification of additional attributes for the FWMMP is proposed as further work and discussed in more detail in Section 12.3. For instance, only 'production or flow rate' and 'distance to transport FW' from the FWMMP were identified as required to calculate the 'total emissions to air' of redistributed waste beer. It has been surmised that the truck emissions per mile are known, but this might not be the case in some circumstances, in which truck emissions per mile would have to be assessed (and could be considered a new unknown attribute). In summary, the information flow diagram informs of the most efficient way to calculate unknown attributes from the known attributes within the FWMMP. It should be noted that if the known/unknown and required/non-required attributes change, the methodology to assess information flows must be applied again.

The information flow diagrams show the relationships between known attributes, and between unknown and known attributes, in all calculation steps. However, it does not inform of the specific mathematical relationships between attributes, which are also needed to complete the assessment process. This is proposed as a further extension of this research in Section 12.3.

10.3 Manufacturer of meat alternatives: Quorn Foods

Quorn Foods is a food company that produces meat-alternative products based on a mycoprotein, achieving a taste, appearance and texture similar to that of meat. Quorn Foods has three manufacturing sites in the UK: Stokesley, Billingham and Methwold. The manufacturing plant visited during this research was the one based at Stokesley, which is also the company headquarters and where mycoprotein is used to manufacture the final product. Quorn Foods products are manufactured through a process that includes fermentation to obtain mycoprotein, mix with other ingredients, steaming, chilling, freezing and packing. The fermentation process is not carried out in Stokesley, thus this production step has not been assessed.

The quantity of total FW generated in Quorn Foods is directly linked to the level of production: in months when production is higher, more FW is generated following the same overall proportion. There are other types of waste not related to food (16% of the total waste), such as cardboard and plastic, which have not been assessed in this research.

10.3.1 Identification and categorisation of FWs, and selection of a FWMS

This section identifies and categorises the different types of FW generated at Quorn Foods' manufacturing plant located in Stokesley, according to the definition of FW provided in

Section 7.2.1 and the boundaries delimited in Section 7.2.2. The different types of FW found are a food solid/slurry mix and food product returns, which account for 63% and 21% of the total waste in the factory respectively.

The FW identified is assessed in the following sub-sections. Possible alternative options from the FWH are suggested as further possibilities when their sustainability performance has been estimated to be higher than that of the suggested alternative. For instance, the suggested FWMS for the food solid/slurry mix cannot be redistribution for human consumption because the FW is unprocessed; nevertheless the potential to use this food material to produce new food products has been assessed. Similarly, some industrial uses are out of the scope of the FWMDT, but they have been assessed independently.

10.3.1.1 Food solid/slurry mix

The food solid/slurry mix is any food material which becomes FW across the production line, e.g. product falling from conveyor belts, trimmings or product stuck onto inner walls of the industrial equipment. Its composition is the same than that of the final product: fungus (mycoprotein), plant-based material, and animal-based products (egg albumen) in low proportions (2-3% by mass of the final product). It is an avoidable waste which could be reduced or eliminated with more appropriate industrial equipment or manufacturing practices.

According to the point in the production line where this FW is generated (Section 7.3), the food solid/slurry mix can be considered a damaged food during preparation generated from unprepared ingredient, prepared ingredient, incomplete food, unprocessed food or processed food, depending on the point in the production line where this FW was generated. It must be pointed out that "damaged food during preparation" refers to the impossibility of reusing the food material to produce more final product following current management practices.

Table 10-10 classifies the food solid/slurry mix according to the nine-stage categorisation presented in Section 7.4. Additionally, the most sustainable FWMS is identified using the FWMDT (Section 7.5): animal feeding. It must be noted that the 'fungus' attribute, from 'origin', was considered as plant based, since it is not under animal by-product regulations.

Currently, the food solid/slurry mix is sent for animal feeding, which is the most sustainable FWMS according to the FWMDT (Figure 7-8). Unfortunately, this FWMS does not provide any economic income at present.

Table 10-10. Categorisation of the food solid/slurry mix and identification of its most sustainable FWMS

Food solid/slurry mix	
Damaged food during preparation generated from unprepared ingredient, prepared ingredient, incomplete food, unprocessed food or processed food	
Edibility	Edible
State	Eatable
Origin	Fungus
Complexity	Mixed product
Animal-product presence	Not in contact with or containing meat, animal by-products or raw eggs
Treatment	Unprocessed
Packaging	Unpackaged
Packaging biodegradability	N/A
Stage of the supply chain	Non-catering waste
Current treatment	Animal feeding
Proposed FWMS	Animal feeding
Other possibilities	Production of foodstuff
Quantity	1000 t/year

The food solid/slurry mix has been considered eatable, as it is generated only because of the inefficiency of the systems rather than to due to problems with the food material. Nevertheless, a more detailed analysis should be carried out to identify all different cases where this FW is generated and assess their state. In case uneatable FW is found (e.g. spilled food onto the floor), this should be classified as a different category of FW (European Commission 2006b), although in this particular case the new FWMS for this FW according to the FWMDT would remain unchanged: animal feeding.

In order to reduce the quantity of FW generated in this category, an investment in improvements in the industrial equipment or manufacturing practices is needed. Alternatively, the FW generated could be recovered and used to produce more final product providing it is still suitable for human consumption and it meets the quality standards required.

10.3.1.2 Food product returns

Food product returns is the final product which cannot be sold to the final consumer because different reasons, including overproduction, incorrect formulation, no traceability and packaging errors. It has the same composition as the final product: fungus (mycoprotein), plant-based material, and animal-based products (egg albumen) in low proportions: 2-3% by mass of the final product. It is an avoidable waste which could be reduced or eliminated with more appropriate manufacturing practices.

According to the point in the production line where this FW is generated (Section 7.3), food product returns can be considered the final food product, which is ultimately wasted.

Table 10-11 classifies food product returns according to the nine-stage categorisation presented in Section 7.4. Additionally, the most sustainable FWMS is identified using the FWMDT (Section 7.5): redistribution for human consumption. It must be noted that the 'fungus' attribute, from 'origin', was considered as plant based, since it is not under animal by-product regulations.

Currently, food product returns is separated from its packaging and sent for anaerobic digestion. The remaining packaging is used to produce refuse-derived fuel. This solution is less sustainable than redistribution for human consumption, which has been identified by using the FWMDT (Figure 7-8).

Table 10-11. Categorisation of food product returns and identification of its most sustainable FWMS

Food product returns	
Final food product	
Edibility	Edible
State	Eatable
Origin	Fungus
Complexity	Mixed product
Animal-product presence	Not in contact with or containing meat, animal by-products or raw eggs
Treatment	Processed
Packaging	Separable from packaging
Packaging biodegradability	N/N
Stage of the supply chain	Non-catering waste
Current treatment	Anaerobic digestion
Proposed FWMS	Redistribution for human consumption
Other possibilities	N/N
Quantity	≈ 360 t/year

Food product returns has been considered eatable, as it corresponds to the final product. However, a more detailed analysis must be carried out before redistributing it for human consumption to identify all cases in which this FW is generated and assess their state. If uneatable FW is found (e.g. its use-by date has passed), it must be classified as a different category of FW, allowing a tailored solution for this type of FW to be applied. In this case, since the product is packaged, there is no risk of uneatable FW contaminating eatable FW.

10.3.2 Analysis of information flows

This section applies the research ideas presented in Sections 9.3 and 9.4 to the upgradeable Quorn Foods' FW identified in Section 10.3.1: food product returns, for which redistribution for human consumption is the FWMS proposed. As a result, a Table of Assessment has been filled and a Results Table has been generated. Finally, the Results Tables have been used to depict optimal information flows which can be seen in information flow diagrams. This allows an easier estimation of results generated from the FWMS proposed based on available information.

10.3.2.1 <u>Food product returns</u>

The attributes needed to model redistribution for human consumption, according to Chapter 8, are listed in the Table of Assessment (Table 10-12). The classification of attributes as known/unknown and required/non-required has been decided based on conversations with staff from Quorn Foods and reasonable assumptions if any information was not available. Consequently, all performance factors and sustainability indicators have been classified as unknown attributes, because redistribution for human consumption has not yet been used for food product returns and therefore the results generated from this FWMS are still unknown. Known attributes are those referring to general characteristics of the product and its manufacturing (e.g. 'edibility', 'density' and 'treatment'), quantity of waste beer generated (360 t/year) and distance to transport it. Required attributes are related to the quantity of product available to redistribute, environmental impacts to air, 'management cost' as economic indicator and 'feeding people' as social indicator. The Table of Assessment shows which attributes are needed to assess each attribute (i.e. 'List of attributes needed') and the number of known and unknown attributes for each attribute to assess.

Table 10-12. Table of Assessment for food product returns

Category of attribute to assess	Attribute to assess	Is the value of the attribute known?	Mark the attributes required	List of attributes needed									Known dependencies	Unknown dependencies
Qualitative food-waste parameters	Edibility	Y												
	State	Y		Edibility									1	
	Treatment	Y												
Primary quantitative food-waste parameters	Production or flow rate	Y	R											
	Biological hazard	Y		State									1	
	Other organic compounds	Y												
	Inorganic content and composition	Y												
Secondary quantitative food-waste parameters	Hazardous materials	Y		State	Other organic compounds	Inorganic content and composition	Biological hazard						4	
	Density	Y												
Process and company variables	Distance to transport food waste	Y		Production or flow rate									1	
Performance factors	Quantity of food redistributed	N	R	Edibility	Treatment	Distance to transport food waste	State	Hazardous materials	Production or flow rate	Biological hazard	Inorganic content and composition	Other organic compounds	9	
Environmental indicators: impacts to air	Total emissions to air	N	R	Distance to transport food waste	Production or flow rate								2	
	CO_2, CH_4, NMVOC, PM<10	N	R	Distance to transport food waste									1	
	N_2O, NOx	N	R	Distance to transport food waste									1	
	Total organic carbon (TOC), dust, PM<2.5	N	R	Distance to transport food waste									1	
Environmental indicators: impacts to water														
Environmental indicators: impacts to soil														
Economic indicators	Management cost	N	R	Production or flow rate	Distance to transport food waste	Quantity of food redistributed							2	1
Social indicators	Support of local economies	N		Production or flow rate	Quantity of food redistributed								1	1
	Job creation	N		Production or flow rate	Quantity of food redistributed								1	1
	Noise	N		Production or flow rate	Quantity of food redistributed	Distance to transport food waste							2	1
	Feeding people	N	R	Production or flow rate	Quantity of food redistributed								1	1
	Traffic	N		Production or flow rate	Quantity of food redistributed	Density	Distance to transport food waste						3	1
												Total	31	6

Once the Table of Assessment has been completed, a Results Table can be prepared by using the methodology explained in Section 9.4. Table 10-13 shows the Results Table for food product returns, in which the order (*n*) in which each attribute must be assessed and the attributes needed for that assessment ('origin attribute') are shown.

Finally, the Results Table has been used to draw an information flow diagram (Figure 10-3) that represents the order of assessment for each attribute and the attributes needed for each assessment. It can be seen that for redistribution for human consumption of food product returns, two calculation steps are needed in order to estimate all required attributes.

Table 10-13. Results Table for food product returns

Results Table

n	Destiny attribute	Origin attribute								
1	Quantity of food redistributed	Edibility	State	Treatment	Production or flow rate	Biological hazard	Inorganic content and composition	Other organic compounds	Hazardous materials	Distance to transport food waste
1	Total emissions to air	Distance to transport food waste	Production or flow rate							
1	CO_2, CH_4, NMVOC, PM<10	Distance to transport food waste								
1	N_2O, NOx	Distance to transport food waste								
1	TOC, dust, PM<2.5	Distance to transport food waste								
2	Management cost	Production or flow rate	Distance to transport food waste	Quantity of food redistributed						
2	Feeding people	Production or flow rate	Quantity of food redistributed							

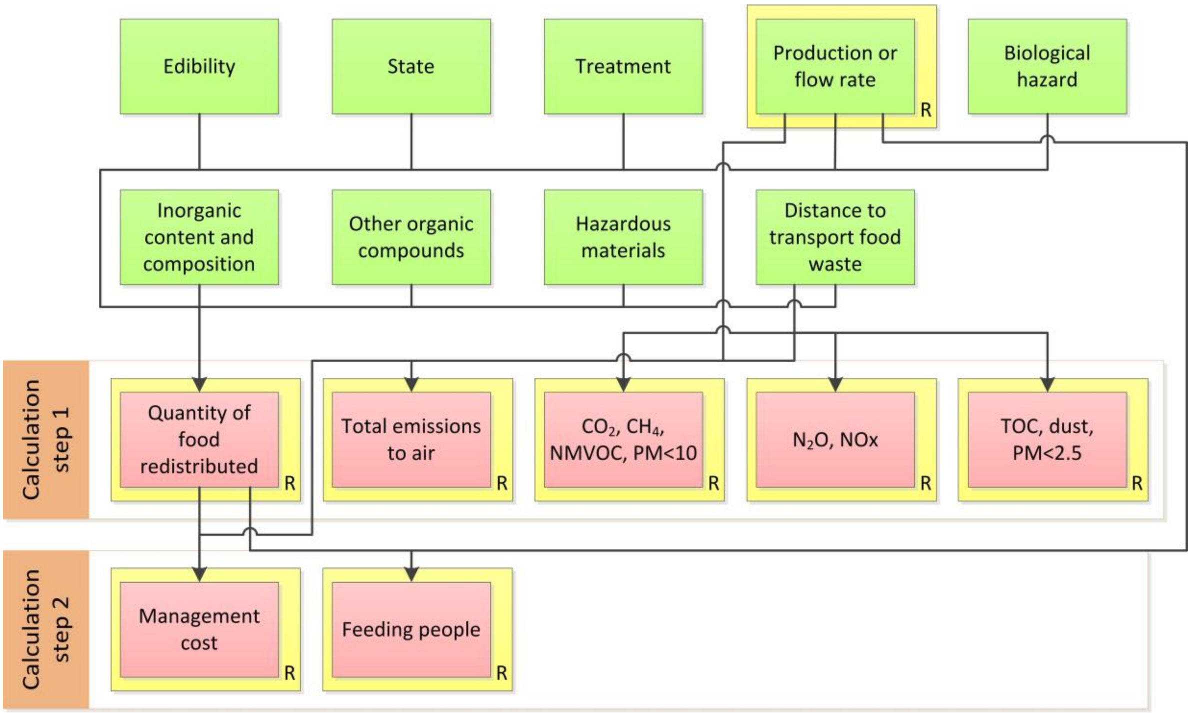


Figure 10-3. Information flow diagram for food product returns

10.3.3 Discussion and conclusions of the research applied to Quorn Foods

The nine-stage categorisation and FWMDT (Chapter 7) have been proved to be useful to analyse Quorn Foods' FW, since one type of FW has been identified to be apt to be managed in a more sustainable way: food product returns.

A more detailed analysis would be beneficial in order to identify sub-types of FW. Afterwards, the assessment should be completed for all new FWs found. This would provide a tailored FWMS for each type of FW. For instance, if a final product for which the use-by date has passed is identified, this FW could be named 'expired food product returns' and its most appropriate FWMS would be anaerobic digestion, unlike the remaining 'food product returns' which could be redistributed.

Additionally, FW principally composed of fungus cannot be strictly classified as plant-based or animal-based material. Consequently, the 'fungus' parameter was introduced, although in practice fungus was considered as plant-based material, since it is not covered by animal by-product regulations.

The systematic analysis carried out with Quorn Foods' FW is also useful to identify the most beneficial strategy for the company in order to improve their FWM. Although food product returns accounts for only 25% of the total food waste, improvements in its management must be prioritised against the food solid/slurry mix because of the following three reasons:

1. Current food product returns management entails an economic cost, whereas the food solid/slurry mix brings neither cost nor benefit.
2. Since food product returns have completed all the manufacturing processes, it has associated a higher use of resources compared to the food solid/slurry mix, which means a higher environmental impact and loss of economic resources.
3. According to the categorisation used to study the different FW streams, the FWMS to manage the food solid/slurry mix is already optimal (animal feeding), but management of food product returns can be still improved as discussed below.

More precise forecasts of the demand of the product would be useful to reduce food product returns which are not sold due to a lack of customer outlet. It is important to notice that the demand of this product varies during the year, with a higher consumer demand in January and February. Alternatively, food product returns should be sold in alternative food markets, or redistributed to people in need or charities, instead of being sent to anaerobic digestion.

Additionally, it would be beneficial to break down the different FW types into more detailed categories, so more FWMSs can be used and adapted to each FW found. Particularly, if eatable food solid/slurry mix is identified, it could be redirected to the production line to manufacture more food product. This should be relatively easy for product that falls from the conveyor belts and trimmings. If a spoilt product is found, a study of the storing conditions must be carried out. Finally, all FW types can also be reduced with more advanced manufacturing systems, which presumably would require large economic investment.

The FWs identified as upgradeable (i.e. food product returns) have been further analysed in order to support an estimation of the results of the proposed FWMSs. A combination of known/unknown and required/non-required attributes has been used to generate information flow diagrams for this FW. Consequently, all calculation steps necessary to estimate results generated from the proposed FWMS have been identified.

Nine known attributes were shown to be needed to assess seven unknown required attributes. As discussed in Section 10.2.3, additional attributes might be needed to complete the assessment process, and mathematical relationships between attributes must be defined. This is proposed as a further extension of this research in Section 12.3. If the known/unknown and required/non-required attributes change, the methodology to assess information flows must be applied again.

10.4 Chapter summary

The case studies presented in this chapter have proven the applicability and usefulness of the research described in this thesis by applying the FWM framework presented in Chapters 7-9 in two real case studies with Molson Coors and Quorn Foods. All FWs generated in both manufacturing plants have been identified according to the definition of FW provided in Section 7.2.1 and the boundaries delimited in Section 7.2.2, and categorised following the nine-stage categorisation presented in Section 7.4. The FWMDT, described in Section 7.5, has been used to identify the most sustainable FWMS for each FW. When an alternative, more sustainable FWMS was found, the FWMMP presented in Chapter 8 has been used to assess it. Finally, information flow diagrams have been created to support the estimation of outputs and implications generated from the proposed FWMS, applying the research ideas presented in Sections 9.3 and 9.4.

It has been demonstrated that the FWM framework can be used to identify alternative, more sustainable FWMSs and aid in the implementation of those alternatives by providing a systematic methodology to estimate implications from FWM.

CHAPTER 11 CONCLUDING DISCUSSIONS

11.1 Introduction

The first section of this chapter discusses the major contributions to research of this thesis. The second part of the chapter analyses the research achievements in the context of the research objectives and scope defined in Chapter 2.

11.2 Research contributions

The research presented in this thesis has investigated solutions to improve sustainability of FWM practices. The most pertinent achievements and contributions to knowledge can be found below:

1. Analysis of FW types and quantities generated in global, European and UK FSCs, along with a determination of the most used solutions to manage FW and their advantages and drawbacks, which have been used to identify common issues in FSCs and weaknesses of existing approaches. As a result, a holistic and comprehensive approach has been used to identify possible improvements and design a novel framework for FWM. A new definition of FW has been provided together with a terminology that has been used throughout this thesis and can also be used by any company or organisation to analyse types of FW generated.
2. Identification of qualitative parameters to describe FW types through a novel nine-stage categorisation process and design of a FWMDT to help determining the most sustainable FWMS for each FW analysed.
3. Design of a procedure to support decision making for FWM that includes the definition of qualitative and quantitative FW parameters, process and company variables, performance factors and sustainability indicators, with the aim of supporting the analysis of FWMSs and predicting the quantitative benefits and disadvantages obtained in each scenario.
4. Evaluation of relationships between all attributes needed to model FW types and FWM processes, which have been used to define a methodology to determine the attributes needed to assess unknown attributes and the order of the assessment. As a result, implications of FWM can be more easily evaluated.

5. Use of the framework to analyse FWM of industrial food manufacturers via two case studies, proving the applicability and usefulness of the research through the identification of more sustainable alternatives for FWM, analysis of the information needed to model their FWM and evaluation of the potential benefits and disadvantages obtained as results.

11.3 Concluding discussion

This section discusses the research results analysing the achievements against the research objectives and scope defined in Chapter 2.

1. *Review relevant literature in order to understand how much food is wasted in an industrial context; and identify the types of food being wasted, how they can be managed and what impacts are associated with them.*

A comprehensive review of the literature has been completed to better understand the magnitude of the FW issue and existing solutions to deal with this problem. In total, 888 sources have been reviewed, which includes journal articles, conference proceedings, books, legislation, reports and websites. 441 sources have been referenced in this thesis.

The first aspect to consider when assessing solutions for FWM is to determine how much FW is generated, and thus, how much FW needs to be managed. Food is wasted in every region of the world, either developed or developing. Globally, around one-third of the edible parts of food are wasted, which accounts for 1.3 billion tonnes every year. In the UK, approximately 10 Mt of FW are generated every year in the post-farm gate part of the FSC. According to the latest data reported, food manufacturers generate 1.7 Mt of this FW. Nevertheless, they also generate a generally overlooked 2.8 Mt of food by-products and 0.7 Mt of food surplus. This massive quantity of industrial FW, along with the fact that 70% is unavoidable, leads to the need to use reactive approaches to find optimal solutions for FWM.

Nevertheless, a large number of initiatives that address the FW problem propose a proactive approach: reduction of current FW levels across the FSC. This, according to the FWH, is the optimal solution for every agent of the FSC, including food manufacturers. Yet, food companies will always generate some FW due to a number of reasons, including overproduction, damages of the food during manufacturing and human errors, and also because most raw materials in the food sector have inedible materials associated, namely food by-products or unavoidable FW.

The ramifications of FWM have been assessed in global, European and UK FSCs based on the most up-to-date and reliable data available. Taking into account the impacts that FW generate not only in the environment, but also in the economy and the society, there is a need to prioritise sustainable alternatives to manage FW that maximises benefits and minimises impacts.

Lastly, common options to manage FW have been described and discussed in the context of the FWH, and their benefits and drawbacks have been identified. The use of each FWMS in each stage of the FSC has been evaluated, concluding that a range of options are currently used, which have very different sustainability performance. In the case of the manufacturing stage, generally FW is homogeneous and its characteristics are known, which facilitates the identification and implementation of more sustainable solutions for FWM. Additionally, food manufacturers have the capability to segregate their FW into different categories and to alter their manufacturing practices, thus they are presumably receptive to implement changes in their FWM that improves their economic performance.

In the UK, most of the data reported on FW types and quantities, and commonly used solutions to manage it, have been published by WRAP. The author believes that standardised methods to measure FW levels and to manage FW are needed to increase sustainability of food systems. Initiatives to reduce FW generation by increasing food manufacturing efficiencies are also necessitated. Lastly, bespoke alternatives to recover value from FW streams sustainably should be developed in the different food sectors.

2. *Provide a systematic categorisation of all types of FW.*

In order to identify the most appropriate solution for a particular FWM scenario, a sound understanding of the characteristics and properties of each FW to be managed is needed. Existing classifications of FW have been reviewed and their applicability have been discussed. It was found that each FW study tends to use its own FW categorisation which causes a lack of comparability amongst different studies. Furthermore, the FW categorisations reviewed are not comprehensive, exhaustive or determinative enough to support the identification of sustainable FWMSs for all types of FW.

As a result, a novel nine-stage FW categorisation has been developed to describe FW types. In each stage of the categorisation, one parameter must be selected according to the characteristic that better describes the FW. The characteristics included in the categorisation have been selected based on a set of criteria: they must be qualitative, simple, specific, determinative and universally applicable. A significant limitation of the nine-stage FW categorisation is that it only considers qualitative characteristics of FW. This has been addressed in the rest of the framework, particularly in the design of the FWMMP, which includes quantitative attributes.

To design an unambiguous and clear categorisation, a terminology has also been defined, which includes not only the definition of the characteristics for each stage of the FW categorisation, but also the definition of the FW concept, boundaries of food systems and types of FW depending on their location in the manufacturing chain. This terminology is applicable to all types of FW falling in the definition of "any food material (including its inedible parts) originally intended to be used to feed humans and not ultimately sold as planned for human consumption by the food business under consideration". Materials such as packaging waste, substances consumed but not ingested (e.g. chewing gum, tobacco) and recreational drugs are out of the scope of this research.

The nine-stage FW categorisation has been used along with a new version of the FWH to identify FWMSs and link them to each FW type. As a result, the FWMDT was developed, which recommends a set of feasible FWMSs ordered by their sustainability performance. The FW categorisation and FWMDT were presented and described in the *International Journal of Food Engineering* (Appendix 2) and the journal of *Waste and Biomass Valorization* (Appendix 6).

Nevertheless, evaluating the relative merits of FWMSs is a complex task. The factors determining which solution is more convenient are difficult to assess and sometimes even difficult to identify, including yields of the processes, proximity of waste management facilities, tax regulations and demand for by-products, amongst many others. It was concluded that a precise breakdown and segregation of FW types provides the best results for FWM, since bespoke solutions can be used for different FWs.

Both the FW categorisation and FWMDT were originally intended to be used by food companies, particularly food manufacturers. This is because both tools are more useful in the early stages of the FSC (i.e. agricultural and manufacturing), where separate collection is generally carried out more effectively, than in the retailing and consumer stages, where FW is often a heterogeneous material that is mixed with MSW. However, although it may provide smaller benefits, the FW categorisation and FWMDT can also be applied to every type of FW from every stage of the FSC. This is why, when designing the stages of the FW categorisation, the stage of the FSC (catering/non-catering FW) was included as a key parameter. In fact, a simplified version of the FW categorisation has been used to analyse consumer FW in two different contexts: student halls in a large university campus and the household level. The results and conclusions of the study for the student halls were published in *Advances in Manufacturing Technology XXX* (Appendix 3) and for the household level in *Procedia CIRP* (Appendix 4), proving the applicability of the FW categorisation in different environments.

The FW categorisation can also be used for monitoring purposes. It provides an easy way to classify FW in a business or a region to assess progress in FW generation and management. Following the systematic approach and terminology described in Chapter 7, comparisons between different companies or geographic areas are also possible.

3. *Develop a framework that can be used by food manufacturers to harmonise different approaches to FWM in order to support the identification of the most sustainable solution to manage each type of FW.*

A thorough analysis of methodologies to support waste management has been carried out to define the state of the art in current approaches. Three main methodologies were identified as the most relevant and widely used: LCA, CBA and MCDM. Although most existing methods focus on one area of sustainability only (i.e. environmental, economic or social implications), recent research is directed towards an integration of methods to consider a wider range of sustainability implications. This is expected to provide more precise and comprehensive waste management models. However, this would also demand a larger quantity of information to model each waste management scenario.

Most research concerning sustainable waste management focuses on MSW, with few studies analysing sustainability implications of FWM. It was identified the need to harmonise different approaches, and preferably to propose a bespoke methodology for FWM that considers the specific needs of food companies. Consequently, a systematic framework for FWM has been designed. This framework was conceived as a supporting methodology that can be used by food manufacturers to assess sustainability implications of FWM. Once the data has been collected through the use of the framework, it can be used to quantitatively evaluate different FWM scenarios and identify stakeholders' preferences with LCA, CBA, MCDM or similar methodologies. Therefore, the framework explained in this thesis provides a holistic, systematic approach to FWM, which can be complemented by other methodologies without overlapping.

The definition of a FW terminology, FW categorisation and the FWMDT were introduced into the framework as the first steps in the assessment process. Once all FWs in a food company were identified, categorised, and a recommendation for their management was given by using the FWMDT, a quantitative analysis was proposed to precisely estimate quantitative outputs of FWM under the FWMS selected. This quantitative analysis was standardised in a stepwise FWMMP. The FWMMP includes several stages to analyse FW parameters, management and company variables, FWM performance factors and sustainability indicators. Each step of the process has been defined and its applicability to assess all information needed to model FWM has been discussed. The stages of the FWMMP were outlined in *Procedia Manufacturing* (Appendix 7).

The FWMMP not only presents a great level of detail, but also is flexible as the user can add or remove information categories to adapt it to their specific needs. On the other hand, the main obstacle of using the FWMMP is the difficulty to collect all data needed and model all possible FWMSs. Consequently, the implementation of the FWMMP in a software tool to automatize and accelerate the assessment process was proposed. The development of such software tool, and the extent to which this is feasible, is discussed as further work in Section 12.3.

4. *Analyse the type and range of information needed to model FWM in order to be able to quantitatively estimate the outcomes generated from management of FW so more informed decisions can be made.*

The FWMMP has been used to classify data needed to model FWM into different categories: information concerning FWs, FWMSs, food companies, performance of FWM processes and sustainability implications of FWM. An extensive analysis of the aforementioned categories was used to identify and classify attributes needed to model FWM scenarios. Both qualitative and quantitative attributes were considered, but priority was given to quantitative attributes. Each attribute identified was independently assessed and its inclusion into the FWMMP was decided upon its relevance to model FWM systems and their previous use in published research or legislation, which confirmed the need to consider the attribute identified. Furthermore, each attribute was linked to each FWMS for which the attribute needed to be defined. One example of a publication was provided for each identified link between an attribute and a FWMS. However, if an attribute was found only in a small number of publications and was considered not relevant by the author, it was not included in the FWMMP. Therefore, attributes collection was undertaken with the aim of providing a determinative and practical FWMMP.

The lists of attributes obtained as a result were intended to be of enough detail to model FWM scenarios precisely. Following the aforementioned procedure, 175 attributes were identified as relevant for FWM, and they were subsequently categorised as explained above. Nevertheless, it is acknowledged that additional attributes may be needed in some circumstances. Consideration of additional attributes is proposed as further work and discussed in Section 12.3. Because of this reason, the lists of attributes are flexible and the FWMMP user can add and remove attributes to adapt them to their specific needs.

Once all FWM attributes were identified, an analysis of them was undertaken to determine relationships between them on a pairwise basis. This was used to identify dependencies between attributes, which is needed to model FWM scenarios. Due to the high number of attributes considered, the different FWMSs analysed and the various types of relationships, defining all possible dependencies is largely complex. To simplify the results, a combination of attributes and a streamlined version of the list of relationships were used to assess anaerobic digestion, composting and thermal treatments with energy recovery. The final results were presented as matrices linking attributes in columns and rows. When all relationships were found, lists of dependencies were developed to determine which attribute from the pair depend on the other attribute. The lists of dependencies were used to draw information flowcharts, which enabled dependencies between all attributes relevant to each FWMS considered to be shown.

Due to the complexity of the information flowcharts, a methodology was developed to assist their use. The methodology allows identifying which attributes are needed to assess the value of an unknown attribute, and if this unknown attribute depends on other unknown attributes, which is the sequence of attributes needed until the list of attributes needed is fully known. It gives as a result a succession of calculation steps needed to assess the unknown attribute, according to the shortest path possible. Nevertheless, the methodology does not inform of the specific mathematical relationships between attributes, which should be defined to complete the analysis of FWM scenarios. This is proposed as further work and discussed in Section 12.3.

5. *Apply the ideas generated in the aforementioned objectives to industrial case studies and thus validate them.*

Two case studies have been used to test the applicability and usefulness of the research reported in this thesis. The case studies have been undertaken with two leading UK food manufacturers: Molson Coors, a brewing company; and Quorn Foods, a manufacturer of meat alternatives. They are both large companies and produce a very different final food product: alcoholic beverages and a solid food. A visit to their manufacturing plants took place during which questionnaires were completed with the assistance of relevant company employees. Once the data was collected, the FWM framework was used to identify alternative options to increase sustainability of their current FWM.

Five different types of FW were identified in Molson Coors. Following the nine-stage categorisation and the FWMDT, two FWMSs were identified as improvable: a more sustainable FWMS was available for waste beer and for filter waste. For both FW types, an analysis of information flows was undertaken to identify optimal information flows that facilitated the estimation of outputs generated from the proposed FWMS. A beneficial strategy for improving FWM was also proposed, in which waste beer was identified as a key FW that could be managed more sustainably. Specifically, a plan was outlined to improve the management of mislabelled beer and reduce its waste generation rate. This plan also explored additional possibilities to those proposed by the use of the FWMDT, as discussed in Section 7.5.1.6, such as options to prevent FW, industrial applications of FW and possibilities to obtain valuable compounds from FW.

Similarly, the FWM framework was used to identify FW types and management opportunities in Quorn Foods. Two types of FW were identified, of which the FWMS for one was improvable, namely food product returns. For this FW, an identification of optimal information flows was undertaken. It was suggested that a more detailed analysis of FW with more sub-categories would provide additional benefits, since the FWM framework can provide specific, distinct results for each FW type. Furthermore, a beneficial strategy for improving FWM was also proposed, in which a more precise forecast of the final product demand was identified as a key practice to reduce the quantity of food product returns.

The case studies were also used to refine the FWM framework. For instance, the assessment of some stages of the FW categorisation was found to be complex, such as ‘edibility’ for spent grain and ‘state’ for waste beer. The specific case of using inedible, plant-based, single or mixed product not in contact with or containing animal-based products, non-catering FW for animal feeding was discussed, concluding that an analysis of each individual case is necessary to complement the use of the FWMDT. Additionally, new parameters such as ‘microorganisms’ and ‘fungus’ were necessary as opposed to plant-based or animal-based material, although they both were considered as plant-based material since they are not affected by animal product legislation. The need of additional attributes and modelling relationships between attributes were identified as the most significant limitations of the FWM framework. Consequently, these aspects have been proposed as further work and discussed in Section 12.3.

While undertaking the research reported in this thesis, there were several opportunities to assess different issues related to FWM. For instance, the use of materials prepared from FW as emulsifiers was investigated, and results were published in the journal of *Materials* (Appendix 5). Also, the valorisation of FW was explored along with other key research challenges facing modern food manufacturers in the context of sustainability; the result of this has been accepted for publication in the book *Smart Innovation, Systems and Technologies* (Appendix 8).

CHAPTER 12 CONCLUSIONS AND FURTHER WORK

12.1 Introduction

This chapter summarises the major conclusions from this research, and suggests several areas where further work could be undertaken to progress the accuracy and industrial readiness of this work.

12.2 Research conclusions

The conclusions drawn from this research are as follows:

1. This research has highlighted the important role that FWM currently plays in achieving more sustainable food systems. Although a large portion of the previous research on sustainable waste management has investigated MSW management, sustainable FWM is a research area that is growing rapidly over recent years. Additionally, recent research trends consider two or even three pillars of sustainability: environmental, economic and social implications of waste management, as opposed to only one type of implication as it was typically considered in more historic research.
2. Currently, food systems are extremely inefficient. Large amounts of FW are generated across FSCs of both developed and developing areas of the world. In the UK, food manufacturers generate a significant amount of FW, which is largely unavoidable and must be managed. There are a number of FWMSs currently used to manage in the food industry, often causing negative sustainability ramifications.
3. There is a growing public and scientific interest in the issue of FW. A range of solutions to tackle the levels of FW produced have been proposed. A number of these solutions follow proactive approaches to reduce FW. However, the importance of not only reducing, but also managing more sustainably the FW that cannot be reduced (i.e. inedible FW), has been highlighted in this research.
4. From the reactive solutions to improve FWM, different methodologies and tools have been reviewed. The most relevant methods include life-cycle assessment

(LCA), cost-benefit analysis (CBA) and multi-criteria decision-making (MCDM). Their applicability and scope have been analysed, and their shortcomings identified. It has been demonstrated that, to successfully integrate the assessment of the different sustainability implications of FWM, a combination of methodologies is beneficial. This brings the challenge of collecting and managing large amounts of data, for which a systematic methodology that supports this data collection and management would be advantageous.

5. A novel framework for FWM has been designed, which includes definitions of FW and food systems; identification of FW types; a qualitative nine-stage FW categorisation; selection of sustainable solutions by using the FWMDT; identification of quantitative attributes for FW, FWM processes, food companies and sustainability implications of FWM; analysis of relationships between attributes; and assessment of information flows. This framework was designed after following a holistic approach to define concepts and methodologies for which there is not yet a global consensus. As a result, this research presents a standardised methodology to identify and assess sustainable solutions for FWM.
6. The FWM framework supports the analysis of different FWM scenarios. It aids in identifying what type and range of information is needed to model FWM systems, allowing the user to follow a systematic methodology to make more informed decisions. The FWM framework was not designed to compete with existing waste management methodologies, such as LCA, CBA and MCDM, but rather to complement their use. Therefore, the output generated from the use of the FWM framework can be used to support the application of any of the aforementioned methodologies.
7. Case studies with two large UK food manufacturers have been used to demonstrate the applicability and usefulness of this research. While conducting the case studies, it was clear that data availability is a serious issue that may affect food companies, complicating estimations of outputs and implications from FWM. Furthermore, in some cases data existed, but was not precise and/or categorised to a sufficient level of detail. This proves the need of a FWM framework to support the identification of data needed for FWM, its collection and use to model FWM systems.
8. The fundamental conclusion drawn from this research is that there is an opportunity to improve value recovery from manufacturing FW streams through a systematic analysis that maximises benefits from FWM whilst reducing environmental, economic and social ramifications.

12.3 Further work

The author suggests the following areas of work where the scope of the research presented in this thesis could be extended.

1. Identification of additional attributes for FWM

An in-depth analysis of FW types and FWM processes was undertaken to identify the most relevant 175 attributes to model FWMSs. Although this set of attributes are determinative and provides a great level of detail to the FWMMP, inclusion of additional attributes into the model could deliver more precise results in certain circumstances. For instance, the list of performance factors was reduced to include only the most relevant attributes. This list could be easily extended to include additional attributes, for instance the concentration of CO_2 in biogas for anaerobic digestion. Similarly, the lowest pH value and highest temperature achieved during the composting process could be relevant process variables to consider, and staff availability could be considered a company variable.

Furthermore, it is recommended that some attributes are itemised in more detailed sub-categories, especially when tailoring the FWMMP to specific food companies. This would be particularly useful for performance factors; for instance, using the specific concentration of nitrogen, phosphorus and potassium instead of 'compost composition'. This was not done because it was intended to keep the FWMMP general with regard to some attributes, so it is applicable in all food sectors. When adapting the FWMMP to specific food companies, it could also be useful to remove some unneeded attributes to compensate the addition of new attributes, so the use of the FWMMP remains manageable.

2. Incorporation of additional FWMSs in the FWMDT and FWMMP

Similarly to the consideration of additional attributes for FWM, further FWMSs could also be added to the FWMDT and FWMMP. This includes FWMSs from the FWH which were not considered in this research because their poor sustainability performance or because they were out of the research scope, such as landspreading, thermal treatment without energy recovery and landfilling, as explained in Section 7.5.1.6.

Of particular interest would be the consideration of industrial uses and extraction of compounds of interest from FW. These options were not included in the FWMDT and FWMMP because they are very specific to the FW type and FWM process, so their consideration would not be possible while the FWM framework is general and applicable to all food sectors. However, the consideration of industrial uses and extraction of compounds of interest would be highly beneficial when tailoring the FWM framework to a specific food company, since these alternatives could provide a large economic benefit to the food industry whilst reducing environmental and social ramifications. Indeed, these options are considered as the most sustainable of the recycling/recovery section of the FWH. When including them in the FWMDT and FWMMP, a number of new attributes specific to the industrial process considered would have to be added in the FWMMP.

3. Consideration of proactive solutions to reduce FW in the FWM framework

In addition to the reactive solutions from the FWH, proactive approaches could also be considered to reduce FW. This was considered outside of the research scope since this research sought to find sustainable solutions to manage FW, not to reduce it. Nevertheless, it is well known that preventing FW from arising is the most sustainable strategy to deal with FW. As an extension of the research scope, common solutions to reduce FW could be explored and arranged according to their sustainability performance, e.g. alternatives that require less energy and water use could be prioritised. Next, they could be added to the FWMDT, linking FW types with common solutions to reduce FW. Additionally, the FWMMP could be extended to include attributes needed to model FW reduction schemes, facilitating the implementation of actions to reduce FW in food companies. When FW reduction is infeasible, the current FWM framework could be used.

4. Mathematical modelling of relationships between attributes

Having identified all relationships and dependencies between attributes, mathematical modelling between attributes would be useful to simulate FWM systems. The outcome of this would be the generation of a set of mathematical equations that allows a quantitative estimation of the value of unknown attributes from the value of known attributes. These mathematical models could be prepared from a review of state-of-art literature in the relevant technologies (i.e. FWMSs) considered. Consequently, the value of performance factors could be calculated from FW parameters and process and company variables, and similarly, sustainability indicators could be evaluated from the performance factors assessed.

Mathematical modelling was considered outside of the scope of this research because of the complexity of modelling all relationships between attributes. 30,450 relationships between attributes were identified, as explained in Section 9.2. Although one mathematical equation could link a number of attributes, it is expected that a large number of mathematical formulae would be needed to link all attributes. Some of the mathematical relationships between attributes are already known, but a number of them would have to be defined by using chemical analyses. Furthermore, mathematical relationships may change as technology develops, for instance a novel anaerobic digestion system could provide higher methane content in the biogas without changing the initial FW.

5. Development of a software-based tool to automatize the assessment process

The FWM framework could be implemented in a software tool to facilitate and accelerate the assessment process. The software tool must model FWMSs, incorporating the mathematical models described above, and deliver as a result an estimate of the sustainability performance of the FWMSs considered.

The software should let the user introduce large amounts of data, use previously introduced data (which could be stored in databases) and simulate industrial processes. Based on these criteria, the software could be developed in Microsoft Excel spreadsheets and MATLAB. It is envisaged that, once the software tool is started, the user would see windows where the data needs to be introduced. This could be done selecting an attribute from a list of options in a dropdown menu, e.g. 'plant based' as a qualitative FW parameter, or typing a numerical value in a box, e.g. '7' for pH as a quantitative primary FW parameter. The user would have to add all relevant data for qualitative and quantitative FW parameters, and process and company variables. Once the information has been collected and added into the system, the data for each FWMS is processed and the values for each FWM performance factors could be calculated by the software by using mathematical models. These mathematical models should be amendable by the user, since different performances could be obtained from the same FWs as technology progresses.

The software tool is envisaged to be used principally by waste managers in the food industry or members of staff with similar roles and duties in the food sector. Due to different backgrounds and significant dissimilarities amongst food manufacturers, the software interface should be simple and user friendly.

A further addition to the software would be the inclusion of a decision-support tool system that, according to the sustainability performances obtained and a pre-established criterion, would recommend the most sustainable FWMS available, maximising positive outcomes and minimising ramifications. The decision-support tool could be designed in a way that the sustainability indicators are weighed according to their relevance in FWM decisions. For instance, GHG emissions could be given a higher priority over acidification to assess environmental performance, or economic implications of FWM could be prioritised over environmental impacts. This prioritisation criterion is subjective and may change over time periods. Consequently, the weighing of indicators should be open to be amended by the user according to their needs and judgement.

6. Creation of a database that could be incorporated into the software-based tool

As a future development of the aforementioned software tool, a database with the value of the most relevant FW parameters could be incorporated in the software. Therefore the user would just have to select the FW to manage from a dropdown menu and its associated FW parameters would be added automatically to the system. For instance, instead of adding the quantitative FW parameters for spent grain, such as carbohydrate content and composition, the user could select 'spent grain' from a menu of FWs, and the software would use values of FW parameters previously introduced in the tool. Consequently, the values of FW parameters must be added by the software developer. These values could be determined using chemical analyses, existing databases or undertaking a review of published literature.

Incorporating databases in the software requires the assumption that FW parameters remain constant for the same FW types in different conditions, e.g. the carbohydrate content and composition of spent grain is unchanged between different batches. This is a safe hypothesis if very precise results are not required, since only small variations in compositions of a FW type in different batches is expected. If significant changes in the value of FW parameters occur, or more precise results are required, the software must let the user to amend values of parameters stored in the database.

7. Testing the applicability of the FWM framework in other food companies and stages of the FSC

Case studies with two large UK food manufacturers have been used to demonstrate the applicability and usefulness of the FWM framework. Although the results obtained were positive, there is a need to further test the FWM framework with a wider range of food industries. It would be particularly interesting to use the FWM framework with small food manufacturers, as opposed to the large companies already assessed, since they may lack in capabilities to identify alternative, more sustainable FWMSs and rely on outdated routines. Additionally, the FWM framework should be tested in diverse food sectors with different FW types.

Although the FWM framework was originally intended to be used principally by food manufacturers, it is potentially usable by any company or person who manages FW. To prove this, the FWM framework must be tested in different stages of the FSC, for instance in farming, wholesaling and retailing environments.

REFERENCES

Abbasi, T. and Abbasi, S.A., 2010. Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Reviews*, 14(3), pp.919–937.

Achillas, C., Moussiopoulos, N., Karagiannidis, A., Banias, G. and Perkoulidis, G., 2013. The use of multi-criteria decision analysis to tackle waste management problems: a literature review. *Waste Management & Research*, 31(2), pp.115–29.

ADBA, 2016a. 2015-2016: When Gas Turned Green. *AD Market Report Summary, December 2016*.

ADBA, 2016b. *Falling income and increasing regulatory scrutiny: attend the R&I Forum*. [Online] available at: <http://adbioresources.org/news/falling-income-and-increasing-regulatory-scrutiny-attend-the-ri-forum> [Accessed Feb. 2017].

ADBA, 2017. *AD map*. [Online] available at: <http://adbioresources.org/map> [Accessed Feb. 2017].

Adenso-Diaz, B. and Mena, C., 2014. Food industry waste management. In: B.K. Tiwari, T. Norton and N.M. Holden, eds., *Sustainable food processing*. Chichester (UK): Wiley-Blackwell, pp.453–462.

Adhikari, B.K., Barrington, S., Martinez, J. and King, S., 2008. Characterization of food waste and bulking agents for composting. *Waste Management*, 28(5), pp.795–804.

Aghajani Mir, M., Taherei Ghazvinei, P., Sulaiman, N.M.N., Basri, N.E.A., Saheri, S., Mahmood, N.Z., Jahan, A., Begum, R.A. and Aghamohammadi, N., 2016. Application of TOPSIS and VIKOR improved versions in a multi criteria decision analysis to develop an optimized municipal solid waste management model. *Journal of Environmental Management*, 166, pp.109–115.

Ahamed, A., Yin, K., Ng, B.J.H., Ren, F., Chang, V.W.-C. and Wang, J.-Y., 2016. Life cycle assessment of the present and proposed food waste management technologies from environmental and economic impact perspectives. *Journal of Cleaner Production*, 131, pp.607–614.

Ahmed, I.I. and Gupta, A.K., 2010. Pyrolysis and gasification of food waste: Syngas characteristics and char gasification kinetics. *Applied Energy*, 87(1), pp.101–108.

Aliyu, S. and Bala, M., 2013. Brewer's spent grain: A review of its potentials and applications. *African Journal of Biotechnology*, 10(3), pp.324–331.

Allesch, A. and Brunner, P.H., 2014. Assessment methods for solid waste management: A literature review. *Waste Management & Research*, 32(6), pp.461–473.

Ameli, M., Mansour, S. and Ahmadi-Javid, A., 2016. A multi-objective model for selecting design alternatives and end-of-life options under uncertainty: A sustainable approach. *Resources, Conservation and Recycling*, 109, pp.123–136.

Amlinger, F., Peyr, S. and Cuhls, C., 2008. Green house gas emissions from composting and mechanical biological treatment. *Waste Management & Research*, 26(1), pp.47–60.

Angelo, A.C.M., Saraiva, A.B., Clímaco, J.C.N., Infante, C.E. and Valle, R., 2017. Life Cycle Assessment and Multi-criteria Decision Analysis: Selection of a strategy for domestic food waste management in Rio de Janeiro. *Journal of Cleaner Production*, 143, pp.744–756.

Anon 2011. *Diatomaceous Earth*. [Online] available at: <https://www.diatomaceousearth.com/> [Accessed May 2015].

Arena, U. and Di Gregorio, F., 2014. A waste management planning based on substance flow analysis. *Resources, Conservation and Recycling*, 85, pp.54–66.

Arvanitoyannis, I.S., 2008. Potential and representatives for application of environmental management systems (EMS) to food industries. In: I.S. Arvanitoyannis, ed., *Waste Management for the Food Industries*. Elsevier Academic Press, pp.3–38. ISBN: 978-0-12-373654-3.

Arvanitoyannis, I.S., Kassaveti, A. and Ladas, D., 2008. Food waste treatment methodologies. In: I.S. Arvanitoyannis, ed., *Waste management for the food industries*. London (UK): Academic Press, pp.345–410. ISBN: 978-0-12-373654-3.

Arvanitoyannis, I.S., Ladas, D. and Mavromatis, A., 2006. Potential uses and applications of treated wine waste: A review. *International Journal of Food Science and Technology*, 41(5), pp.475–487.

Aye, L. and Widjaya, E.R., 2006. Environmental and economic analyses of waste disposal options for traditional markets in Indonesia. *Waste Management*, 26(10), pp.1180–1191.

Babalola, M.A., Lin, Y.-P. and Chang, C.-Y., 2015. A Multi-Criteria Decision Analysis of Waste Treatment Options for Food and Biodegradable Waste Management in Japan. *Environments*, 2, pp.471–488.

Barilla Center for Food & Nutrition, 2012. *Food waste: causes, impacts and proposals*.

Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V., Pavlostathis, S.G., Rozzi, A., Sanders, W.T., Siegrist, H. and Vavilin, V. a., 2002. The IWA Anaerobic Digestion Model No 1 (ADM1). *Water Science and Technology*, 45(10), pp.65–73.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A. and Aghdasi, M., 2010. PROMETHEE: A comprehensive literature review on methodologies and applications. *European Journal of Operational Research*, 200(1), pp.198–215.

Bergeron, F.C., 2017. Analytical method of waste allocation in waste management systems: Concept, method and case study. *Environmental Impact Assessment Review*, 62, pp.35–48.

Bernstad, A. and La Cour Jansen, J., 2012. Review of comparative LCAs of food waste management systems - Current status and potential improvements. *Waste Management*, 32(12), pp.2439–2455.

Bernstad Saraiva Schott, A. and Andersson, T., 2015. Food waste minimization from a life-cycle perspective. *Journal of Environmental Management*, 147, pp.219–226.

Bernstad Saraiva Schott, A. and Cánovas, A., 2015. Current practice, challenges and potential methodological improvements in environmental evaluations of food waste prevention – A discussion paper. *Resources, Conservation and Recycling*, 101, pp.132–142.

Bertanza, G., Baroni, P. and Canato, M., 2016. Ranking sewage sludge management strategies by means of Decision Support Systems: A case study. *Resources, Conservation and Recycling*, 110, pp.1–15.

Beylot, A., Vaxelaire, S., Zdanevitch, I., Auvinet, N. and Villeneuve, J., 2015. Life Cycle Assessment of mechanical biological pre-treatment of Municipal Solid Waste: A case study. *Waste Management*, 39, pp.287–294.

Bilska, B., Wrzosek, M., Kołożyn-Krajewska, D. and Krajewski, K., 2016. Risk of food losses and potential of food recovery for social purposes. *Waste Management*, 52, pp.269–277.

Binder, C.R., Quirici, R., Domnitcheva, S. and Stäubli, B., 2008. Smart labels for waste and resource management: An integrated assessment. *Journal of Industrial Ecology*, 12(2), pp.207–228.

Biogas-info.co.uk, 2015. *Regulation*. [Online] available at: <http://www.biogas-info.co.uk/about/regulation/> [Accessed Nov. 2015].

BiPRO, 2008. *Organisation of awareness-raising events concerning the application and enforcement of community legislation on landfills. Final report*. November.

den Boer, E., Brouwer, F., Schroten, A. and van Essen, H., 2009. *Are trucks taking their toll? The environmental, safety and congestion impacts of lorries in the EU*. Delft (The Netherlands).

de Boer, L., Wegen, L. van der and Telgen, J., 1998. Outranking methods in support of supplier selection. *European Journal of Purchasing & Supply Management*, 4(2–3), pp.109–118.

Del Borghi, A., Gallo, M. and Del Borghi, M., 2009. A survey of life cycle approaches in waste management. *International Journal of Life Cycle Assessment*, 14(7), pp.597–610.

Börjesson, P. and Berglund, M., 2007. Environmental systems analysis of biogas systems-Part II: The environmental impact of replacing various reference systems. *Biomass and Bioenergy*, 31(5), pp.326–344.

Brändli, R.C., Bucheli, T.D., Kupper, T., Furrer, R., Stahel, W. a, Stadelmann, F.X. and Tarradellas, J., 2007a. Organic pollutants in compost and digestate. Part 1. Polychlorinated biphenyls, polycyclic aromatic hydrocarbons and molecular markers. *Journal of Environmental Monitoring*, 9(5), pp.456–464.

Brändli, R.C., Kupper, T., Bucheli, T.D., Zennegg, M., Huber, S., Ortelli, D., Müller, J., Schaffner, C., Iozza, S., Schmid, P., Berger, U., Edder, P., Oehme, M., Stadelmann, F.X. and Tarradellas, J., 2007b. Organic pollutants in compost and digestate. Part 2. Polychlorinated dibenzo-p-dioxins, and -furans, dioxin-like polychlorinated biphenyls, brominated flame retardants, perfluorinated alkyl substances, pesticides, and other compounds. *Journal of Environmental Monitoring*, 9(5), pp.465–472.

Bräutigam, K.-R., Jörissen, J. and Priefer, C., 2014. The extent of food waste generation across EU-27: Different calculation methods and the reliability of their results. *Waste Management & Research*, 32(8), pp.683–694.

Bridgwater, E. and Quested, T., 2013. *Synthesis of Food Waste Compositional Data 2012. Final Report*. WRAP. ISBN: 978-1-84405-460-2.

British Standards Institution, 2011. *PAS 100:2011 Specification for Composted Materials*. March. ISBN: 978-0-580-65307-0.

British Standards Institution, 2014. *PAS 110:2014. Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials*. July. ISBN: 978-0-580-82661-0.

Brunner, P.H. and Rechberger, H., 2014. Waste to energy - key element for sustainable waste management. *Waste Management*, 37, pp.3–12.

Bujak, J. and Sitarz, P., 2016. Incineration of animal by-products - The impact of selected parameters on the flux of flue gas enthalpy. *Waste Management*, 50, pp.309–323.

Bujak, J.W., 2015. New insights into waste management – Meat industry. *Renewable Energy*, 83, pp.1174–1186.

Buksti, M., Fremming, T., Juul, S., Grandjean, F. and Christensen, S., 2015. *Surplus Food Redistribution System. Feasibility Final Report*. Wageningen (The Netherlands).

Buragohain, B., Mahanta, P. and Moholkar, V.S., 2012. Thermodynamic Approach to Design and Optimization of Biomass Gasifier Utilizing Agro-Residues. In: A. Karagiannidis, ed., *Waste to Energy. Opportunities and Challenges for Developing and Transition Economies*. Springer, pp.182–183.

Calaf-Forn, M., Roca, J. and Puig-Ventosa, I., 2014. Cap and trade schemes on waste management: A case study of the Landfill Allowance Trading Scheme (LATS) in England. *Waste Management*, 34(5), pp.919–928.

Carbon Trust, 2012. *Carbon footprinting.* Available at: <https://www.carbontrust.com/media/44869/j7912_ctv043_carbon_footprinting_aw_interactive.pdf> [Accessed Nov. 2014], March.

Caton, P. a., Carr, M. a., Kim, S.S. and Beautyman, M.J., 2010. Energy recovery from waste food by combustion or gasification with the potential for regenerative dehydration: A case study. *Energy Conversion and Management*, 51(6), pp.1157–1169.

Chabada, L., Dreyer, H.C., Romsdal, A. and Powell, D.J., 2013. Sustainable Food Supply Chains: Towards a Framework for Waste Identification. In: C. Emmanouilidis, M. Taisch and D. Kiritsis, eds., *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services*. Berlin, Heidelberg (Germany): Springer Berlin Heidelberg, pp.208–215.

Chaboud, G. and Daviron, B., 2017. Food losses and waste: Navigating the inconsistencies. *Global Food Security*, 12(June 2016), pp.1–7.

Chadderton, C., Foran, C.M., Rodriguez, G., Gilbert, D., Cosper, S.D. and Linkov, I., 2016. Decision support for selection of food waste technologies at military installations. *Journal of Cleaner Production*, 141, pp.267–277.

Chang, J.I. and Chen, Y.J., 2010. Effects of bulking agents on food waste composting. *Bioresource Technology*, 101(15), pp.5917–5924.

Chang, J.I. and Hsu, T.E., 2008. Effects of compositions on food waste composting. *Bioresource Technology*, 99(17), pp.8068–8074.

Chang, J.I., Tsai, J.J. and Wu, K.H., 2006. Thermophilic composting of food waste. *Bioresource Technology*, 97(1), pp.116–122.

Chang, N.-B., Pires, A. and Martinho, G., 2011. Empowering Systems Analysis for Solid Waste Management: Challenges, Trends, and Perspectives. *Critical Reviews in Environmental Science and Technology*, 41(16), pp.1449–1530.

Chapagain, A. and James, K., 2011. *The water and carbon footprint of household food and drink waste in the UK*. WRAP. ISBN: 978-1-84405-464-0.

Chapagain, A. and Orr, S., 2008. *UK Water Footprint: the impact of the UK's food and fibre consumption on global water resources. Volume one*. [Online] available at: <http://waterfootprint.org/media/downloads/Orr_and_Chapagain_2008_UK_waterfootprint-vol1.pdf> [Accessed Jul. 2014], WWF, Surrey (UK).

Chen, C.C., 2010. A performance evaluation of MSW management practice in Taiwan. *Resources, Conservation and Recycling*, 54(12), pp.1353–1361.

Chen, H., Jiang, W., Yang, Y., Yang, Y. and Man, X., 2017. State of the art on food waste research: a bibliometrics study from 1997 to 2014. *Journal of Cleaner Production*, 140, pp.840–846.

Chen, T., Jin, Y., Qiu, X. and Chen, X., 2014. A hybrid fuzzy evaluation method for safety assessment of food-waste feed based on entropy and the analytic hierarchy process methods. *Expert Systems with Applications*, 41(16), pp.7328–7337.

Chen, T., Jin, Y. and Shen, D., 2015. A safety analysis of food waste-derived animal feeds from three typical conversion techniques in China. *Waste Management*, 45, pp. 42-50.

Chen, X., Romano, R.T. and Zhang, R., 2010. Anaerobic digestion of food wastes for biogas production. *International Journal of Agricultural and Biological Engineering*, 3(4), pp.61–72.

Cherubini, F., Bargigli, S. and Ulgiati, S., 2009. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. *Energy*, 34(12), pp.2116–2123.

Chiu, S.L.H. and Lo, I.M.C., 2016. Reviewing the anaerobic digestion and co-digestion process of food waste from the perspectives on biogas production performance and environmental impacts. *Environmental Science and Pollution Research*, 23, pp. 24435–24450.

Chong, Y.T., Teo, K.M. and Tang, L.C., 2016. A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability. *Renewable and Sustainable Energy Reviews*, 56, pp.797–809.

Christensen, T.H., Bhander, G., Lindvall, H., Larsen, A.W., Fruergaard, T., Damgaard, A., Manfredi, S., Boldrin, A., Riber, C. and Hauschild, M., 2007. Experience with the use of LCA-modelling (EASEWASTE) in waste management. *Waste Management & Research*, 25(3), pp.257–262.

Clemente, R., Pardo, T., Madejón, P., Madejón, E. and Bernal, M.P., 2015. Food byproducts as amendments in trace elements contaminated soils. *Food Research International*, 73, pp.176–189.

Climenhaga, M.A., 2008. *Anaerobic digestion of catering wastes*. University of Southampton. [Online] available at: <http://eprints.soton.ac.uk/73611/> [Accessed Jun. 2015].

Commission of the European Communities, 2008. *Green Paper on the management of bio-waste in the European Union {SEC(2008) 2936}*. Brussels (Belgium).

Cooperband, L., 2002. *The Art and Science of Composting. A resource for farmers and compost producers*. Center for Integrated Agricultural Systems, University of Wisconsin-Madison. 29 March.

Corrado, S., Ardente, F., Sala, S. and Saouter, E., 2017. Modelling of food loss within life cycle assessment: From current practice towards a systematisation. *Journal of Cleaner Production*, 140, pp.847–859.

Cristóbal, J., Limleamthong, P., Manfredi, S. and Guillén-Gosálbez, G., 2016. Methodology for combined use of data envelopment analysis and life cycle assessment applied to food waste management. *Journal of Cleaner Production*, 135, pp.158–168.

Darlington, R. and Rahimifard, S., 2006. A responsive demand management framework for the minimization of waste in convenience food manufacture. *International Journal of Computer Integrated Manufacturing*, 19(8), pp.751–761.

Deepanraj, B., Sivasubramanian, V. and Jayaraj, S., 2015. Experimental and kinetic study on anaerobic digestion of food waste: The effect of total solids and pH. *Journal of Renewable and Sustainable Energy*, 7(6), p.63104.

Defra, 2007. *Waste strategy for England 2007*. [Online] available at: <http://archive.defra.gov.uk/environment/waste/strategy/strategy07/documents/waste07-strategy.pdf > [Accessed Jun. 2014].

Defra, 2010. *Environmental Permitting Guidance. The Landfill Directive. For the Environmental Permitting (England and Wales) Version 3.1*. March.

Defra, 2011a. *Controls on Animal By-Products: Guidance on Regulation (EC) 1069/2009 and accompanying implementing Regulation (EC) 142/2011, enforced in England by the Animal By-Products (Enforcement) (England) Regulations 2011*. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69458/pb13688-animal-by-products-controls-111130.pdf> [Accessed Oct. 2014].

Defra, 2011b. *Government Review of Waste Policy in England 2011*. London (UK). [Online] available at: <http://www.devon.gov.uk/print/core-doc-k6-government-review-of-waste-policy-2011.pdf> [Accessed Oct. 2014].

Defra, 2011c. *Guidance on applying the Waste Hierarchy*. June. London (UK).

Defra, 2012. *Landfill Allowance Trading Scheme*.

Defra, 2013a. *Food Statistics Pocketbook 2012 - in year update*. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/183302/foodpocketbook-2012edition-09apr2013.pdf> [Accessed Sep. 2014], York (UK).

Defra, 2013b. *Incineration of Municipal Solid Waste*, [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221036/pb13889-incineration-municipal-waste.pdf> [Accessed Sep. 2014], February.

Defra, 2015. *Statistics on waste managed by local authorities in England in 2014-2015*, [Online] available at: <https://www.cumbria.gov.uk/elibrary/Content/Internet/538/755/1929/42587134020.pdf> [Accessed Jan. 2016], 1 December.

Defra, 2016. Food Statistics Pocketbook 2016. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/608426/foodpocketbook-2016report-rev-12apr17.pdf> [Accessed Jan. 2017].

Defra, n.d. *Feeding catering waste to farmed animals is ILLEGAL*. London (UK).

Defra, Department of Agriculture Environment and Rural Affairs (Northern Ireland), Welsh Assembly Government and Government, T.S., 2016. Agriculture in the United Kingdom 2015. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/208436/auk-2012-25jun13.pdf> [Accessed Jun. 2016].

Defra, Environment Agency and WRAP, 2011. *Applying the Waste Hierarchy: evidence summary*. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69404/pb13529-waste-hierarchy-summary.pdf> [Accessed Jun. 2014], June, London (UK).

Defra and Food Standards Agency (FSA), 2011. *Guidance on the application of date labels to food*. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69316/pb132629-food-date-labelling-110915.pdf> [Accessed Jun. 2014], September.

Defra and Government Statistical Service, 2015. *Fly-tipping statistics for England, 2014/15*. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/469566/Flycapture_201415_Statistical_release_FINAL.pdf> [Accessed Nov. 2015], 20 October.

Downing, E., Kennedy, S. and Fell, M., 2014. Food Banks and Food Poverty. House of Commons Library. SN06657. *Library House of Commons*, April.

Dyer, J.S., Fishburn, P.C., Steuer, R.E., Wallenius, J. and Zionts, S., 1992. Multiple Criteria Decision Making, Multiattribute Utility Theory: The Next Ten Years. *Management Science*, 38(5), pp.645–654.

EARTO, 2014. *The TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations*. [Online] available at: <http://www.earto.eu/fileadmin/content/03_Publications/The_TRL_Scale_as_a_R_I_Policy_Tool_-_EARTO_Recommendations_-_Final.pdf> [Accessed Jan. 2015], April.

Edjabou, M.E., Jensen, M.B., Götze, R., Pivnenko, K., Petersen, C., Scheutz, C. and Astrup, T.F., 2015. Municipal solid waste composition: sampling methodology, statistical analyses, and case study evaluation. *Waste Management*, 36, pp.12–23.

Ekvall, T., Assefa, G., Björklund, A., Eriksson, O. and Finnveden, G., 2007. What life-cycle assessment does and does not do in assessments of waste management. *Waste Management*, 27(8), pp.989–996.

Emkes, H., Coulon, F. and Wagland, S., 2015. A decision support tool for landfill methane generation and gas collection. *Waste Management*, 43, pp.307-318.

Environment Agency, 2004. *Review of agricultural waste research and development projects*. *Agricultural Waste Stakeholders' Forum*. ISBN: 1844323455.

Environment Agency, 2010. Understanding the Landfill Directive. Regulatory Guidance Series, No LFD 1. *Environmental Permitting Regulations (England and Wales)*. [Online] available at: <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296536/LIT_8286_f89fa7.pdf> [Accessed Feb. 2015], March.

Environment Agency, 2013. *How to comply with your landspreading permit. TGN EPR 8.01*.

Bristol (UK).

Environment Agency, 2016. *Standard rules for the Environmental Permitting Regulations: consultation no. 14. Landspreading business engagement assessment: summary of responses and decisions*. August.

Environmental Protection Agency, 2004. *Landspreading of Organic Waste - Guidance on Groundwater Vulnerability Assessment of Land*. Johnstown Castle (Ireland). ISBN: 1-84095-110-9. ISBN: 1-84095-281-4.

Environmental Protection Agency, 2008. *BAT Guidance Note on Best Available Techniques for the Brewing, Malting & Distilling Sector*. Wexford (Ireland). ISBN: 1-84095-281-4

Environmental Protection UK, 2016. *Air pollution sources*. [Online] available at: <http://www.environmental-protection.org.uk/policy-areas/air-quality/about-air-pollution/air-pollution-sources/> [Accessed Jun. 2016].

Eriksson, M. and Spångberg, J., 2017. Carbon footprint and energy use of food waste management options for fresh fruit and vegetables from supermarkets. *Waste Management*, 60, pp.786–799.

Eriksson, M., Strid, I. and Hansson, P.-A., 2015. Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study. *Journal of Cleaner Production*, 93, pp.115–125.

Eriksson, O., Bisaillon, M., Haraldsson, M. and Sundberg, J., 2014. Integrated waste management as a mean to promote renewable energy. *Renewable Energy*, 61, pp.38–42.

Eriksson, O., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.-O., Granath, J., Carlsson, M., Baky, A. and Thyselius, L., 2002. ORWARE—a simulation tool for waste management. *Resources, Conservation and Recycling*, 36(4), pp.287–307.

Eshet, T., Ayalon, O. and Shechter, M., 2005. A critical review of economic valuation studies of externalities from incineration and landfilling. *Waste Management & Research*, 23(6), pp.487–504.

European Commision, 2015. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the loop - An EU action plan for the circular economy. Com(2015)*.

European Commission, 2000. Commission Decision on the European List of Waste (COM 2000/532/EC). *Official Journal of the European Communities*, 2000D0532(01.01.2002), pp.1–31.

European Commission, 2005a. *Reference Document on Best Available Techniques in the slaughterhouses and animal by-products industries*. *Integrated Pollution Prevention and Control*.

European Commission, 2005b. Regulation (EC) No 183/2005 of the European Parliament and of the Council of 12 January 2005 laying down requirements for feed hygiene. (Text with EEA relevance). *Official Journal of the European Union*, (February), p.L 35/1-22.

European Commission, 2006a. *Reference Document on Best Available Techniques for the Waste Treatments Industries*. *Integrated Pollution Prevention and Control*. August.

European Commission, 2006b. *Reference Document on Best Available Techniques in the food, drink and milk industries*. *Integrated Pollution Prevention and Control*. August.

European Commission, 2006c. *Reference Document on the Best Available Techniques for Waste Incineration. Integrated Pollution Prevention Control.* August.

European Commission, 2010. *Communication from the Commission to the Council and the European Parliament on future steps in bio-waste management in the European Union {SEC(2010) 577}*. Brussels (Belgium).

European Commission, 2011. Commission Regulation (EU) No 142/2011 of 25 February 2011. *Official Journal of the European Union*, L 54, pp.1–254.

European Commission, 2013. *Annexes to the Proposal for a Directive of the European Parliament and of the Council on the Reduction of National Emissions of Certain Atmospheric Polluants and Amending Directive 2003/35/EC*.

European Commission, 2014. *Guide to Cost-benefit Analysis of Investment Projects: Economic appraisal tool for Cohesion Policy 2014-2020*. *Publications Office of the European Union*. December. ISBN: 978-92-79-34796-2.

European Commission, 2017. *FoRWaRD – Food Recovery and Waste Reduction*. Lifelong Learning Programme. [Online] available at: <http://foodrecoveryproject.eu/> [Accessed Jan. 2017].

European Commission. Directorate-General for Health and Food Safety, 2016. EU Platform on Food Losses and Food Waste. Terms of Reference (ToR) 26. *Food and feed safety, innovation. Food information and composition, food waste*, 26 April.

European Commission (DG ENV), 2010. *Preparatory Study on Food Waste Across EU 27*. October. ISBN : 978-92-79-22138-5.

European Commission (EC), 2002. Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002 on undesirable substances in animal feed. *Official Journal of the European Union*, L140, pp.10–21.

European Commission Framework Programme 7, 2017. *FUSIONS (Food Use for Social Innovation by Optimising Waste Prevention Strategies)*. [Online] available at: <http://www.eu-fusions.org/> [Accessed Jan. 2017].

European Commission SWA-Tool Consortium, 2004. *Methodology for the Analysis of Solid Waste (SWA-Tool). User version*. [Online] available at: <https://www.wien.gv.at/meu/fdb/pdf/swa-tool-759-ma48.pdf> [Accessed Jan. 2016], Vienna (Austria).

European Environment Agency, 2015. *NEC Directive status report 2014*. ISSN: 1725-2237.

European Parliament, 2006. Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste. *Official Journal of the European Union*, April(11), p.L 114/9-21.

FAO, 1996. *Rome Declaration on World Food Security and Plan of Action*. [Online] available at: <http://www.fao.org/docrep/003/w3613e/w3613e00.htm> [Accessed Jun. 2014].

FAO, 2002. *The State of Food Insecurity in the World 2002*. Rome (Italy). ISBN: 92-5-104815-0.

FAO, 2011. *Global food losses and food waste - Extent, causes and prevention*. Rome (Italy). ISBN: 978-92-5-107205-9.

FAO, 2013a. *Food Wastage Footprint. Impacts on natural resources. Technical Report*. [Online] available at: <http://www.fao.org/docrep/018/ar429e/ar429e.pdf> [Accessed Jun. 2014].

FAO, 2013b. *Toolkit. Reducing the Food Wastage Footprint*. ISBN: 978-92-5-107741-2.

FAO, 2014a. *Definitional Framework of Food Loss. Working paper*. [Online] available at: <http://www.fao.org/fileadmin/user_upload/save-food/PDF/FLW_Definition_and_Scope_2014.pdf> [Accessed Jun. 2014], 27 February, Rome (Italy).

FAO, 2014b. *Food Loss Assessments: Causes and Solutions. Case Studies in Small-scale Agriculture and Fisheries Subsectors*. [Online] available at: <http://www.fao.org/fileadmin/user_upload/save-food/PDF/Kenya_Food_Loss_Studies.pdf> [Accessed Jan. 2015], Rome (Italy).

FAO, 2014c. *Food Wastage Footprint: Full cost-accounting. Final report*. ISBN: 978-92-5-108512-7.

FAO, 2014d. *Mitigation of food wastage. Societal costs and benefits*. ISBN: 978-92-5-108510-3.

FAO, 2016. *Towards a new green revolution*. [Online] available at: <http://www.fao.org/docrep/x0262e/x0262e06.htm> [Accessed Jan. 2017].

FAO, IFAD and WFP, 2015. *The State of Food Insecurity in the World: Meeting the 2015 international hunger targets: taking stock of uneven progress*. Rome (Italy). ISBN: 978-92-5-108785-5.

Farmer, T.D., Shaw, P.J. and Williams, I.D., 2015. Destined for indecision? A critical analysis of waste management practices in England from 1996 to 2013. *Waste Management*, 39, pp.266–276.

Fava, F., Zanaroli, G., Vannini, L., Guerzoni, E., Bordoni, A., Viaggi, D., Robertson, J., Waldron, K., Bald, C., Esturo, A., Talens, C., Tueros, I., Cebrián, M., Sebok, A., Kuti, T., Broeze, J., Macias, M. and Brendle, H.G., 2013. New advances in the integrated management of food processing by-products in Europe: Sustainable exploitation of fruit and cereal processing by-products with the production of new food products (NAMASTE EU). *New Biotechnology*, 30(6), pp.647–655.

Ferraz, E., Coroado, J., Silva, J., Gomes, C. and Rocha, F., 2011. Manufacture of Ceramic Bricks Using Recycled Brewing Spent Kieselguhr. *Materials and Manufacturing Processes*, 26(10), pp.1319–1329.

Finnveden, G., Bjorklund, A., Moberg, A., Ekvall, T. and Moberg, A., 2007. Environmental and economic assessment methods for waste management decision-support: possibilities and limitations. *Waste Management & Research*, 25(3), pp.263–269.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. and Suh, S., 2009. Recent developments in Life Cycle Assessment. *Journal of Environmental Management*, 91(1), pp.1–21.

Fisgativa, H., Tremier, A. and Dabert, P., 2015. Characterizing the variability of food waste quality: A need for efficient valorisation through anaerobic digestion. *Waste*

Management, 50, pp.264–274.

Fisher, K., James, K., Sheane, R., Nippress, J., Allen, S., Cherruault, J.-Y., Fishwick, M., Lillywhite, R. and Sarrouy, C., 2013. *An initial assessment of the environmental impact of grocery products*. WRAP, March.

Flores, R.A., Shanklin, C.W., Loza-Garay, M. and Wie, S.H., 1999. Quantification and characterization of food processing wastes/residues. *Compost Science & Utilization*, 7(1), pp.63–71.

Food Loss + Waste Protocol, 2016. *Food Loss and Waste Accounting and Reporting Standard*. ISBN: 978-1-56973-892-4.

Food Safety Authority of Ireland, 2008. *Food safety implications of land-spreading agricultural, municipal and industrial organic materials on agricultural land used for food production in Ireland*. ISBN: 1-904465-59-5.

Food Standards Agency (FSA), 2014. *Feed law. Practice Guidance (England)*. April.

Food Standards Agency (FSA), 2015. *Animal feed legislation and guidance*. [Online] available at: <http://www.food.gov.uk/business-industry/farmingfood/animalfeed/animalfeedlegislation> [Accessed Nov. 2015].

FoodDrinkEurope, 2014. *Preventing food wastage in the food and drink sector. Europe's food and drink manufactureres take action to prevent food wastage*. [Online] available at: <http://www.fooddrinkeurope.eu/uploads/publications_documents/Preventing_food_wastage_in_the_food_and_drink_sector.pdf> [Accessed Dec. 2014], Brussels (Belgium).

Friends of the Earth, 2010. *More jobs, less waste: Potential for job creation through higher rates of recycling in the UK and EU*. [Online] available at: <http://www.foe.co.uk/resource/reports/jobs_recycling.pdf> [Accessed Jan. 2015], September.

FUSIONS, 2014. *FUSIONS Definitional Framework for Food Waste. Final report*, 3 July, ISBN: 978-91-7290-331-9.

FUSIONS, 2015. *Criteria for and baseline assessment of environmental and socio-economic impacts of food waste. Final report*. 13 November. ISBN: 978-3-900932-32-9.

FUSIONS, 2016. *Estimates of European food waste levels*. Paris (France). ISBN: 978-91-88319-01-2.

Galanakis, C.M., 2012. Recovery of high added-value components from food wastes: Conventional, emerging technologies and commercialized applications. *Trends in Food Science and Technology*, 26(2), pp.68–87.

Galanakis, C.M., 2015. *Food Waste Recovery. Processing Technologies and Industrial Techniques*. Elsevier. ISBN: 978-0-12-800351-0.

Galanakis, C.M., Martinez-saez, N., Dolores, M., Barba, F.J. and Mitropoulou, V.S., 2015. Patented and commercialized applications. In: C.M. Galanakis, ed., *Food waste recovery. Processing Technologies and Industrial Techniques*. Elsevier, pp.337–360. ISBN: 978-0-12-800351-0.

Garcia-Garcia, G., Woolley, E. and Rahimifard, S., 2015. A Framework for a More Efficient Approach to Food Waste Management. *International Journal of Food Engineering*, 1(1), pp.65–72.

Garcia-Garcia, G., Woolley, E. and Rahimifard, S., 2017. Optimising industrial food waste management. *Procedia Manufacturing*, 8, pp.432–439.

Garcia-Garcia, G., Woolley, E., Rahimifard, S., Colwill, J., White, R. and Needham, L., 2016. A Methodology for Sustainable Management of Food Waste. *Waste and Biomass Valorization*, doi:10.1007/s12649-016-9720-0.

Garnett, T., 2008. *Cooking up a storm and our changing climate*. *Food Climate Research Network*. [Online] available at: <http://www.fcrn.org.uk/fcrnPublications/publications/PDFs/CuaS_web.pdf> [Accessed Feb. 2015].

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy*, 36, pp.S23–S32.

Gebrezgabher, S.A., Meuwissen, M.P.M., Prins, B.A.M. and Lansink, A.G.J.M.O., 2010. Economic analysis of anaerobic digestion-A case of Green power biogas plant in the Netherlands. *NJAS - Wageningen Journal of Life Sciences*, 57(2), pp.109–115.

Gendebien, A., Ferguson, R., Brink, J., Horth, H., Sullivan, M., Davis, R., Brunet, H., Dalimier, F., Landrea, B., Krack, D., Pero, J. and Orsi, C., 2001. *Survey of wastes spread on land*.

Gentil, E.C., Damgaard, A., Hauschild, M., Finnveden, G., Eriksson, O., Thorneloe, S., Kaplan, P.O., Barlaz, M., Muller, O., Matsui, Y., Ii, R. and Christensen, T.H., 2010. Models for waste life cycle assessment: Review of technical assumptions. *Waste Management*, 30(12), pp.2636–2648.

Gerardi, M.H., 2003. *The Microbiology of Anaerobic Digesters*. *Vasa*. Hoboken, New Jersey, USA: John Wiley & Sons, Inc.

Girotto, F., Alibardi, L. and Cossu, R., 2015. Food waste generation and industrial uses: A review. *Waste Management*, 45, pp.32–41.

Giuseppe, A., Mario, E. and Cinzia, M., 2014. Economic benefits from food recovery at the retail stage: An application to Italian food chains. *Waste Management*, 34(7), pp.1306–1316.

Goedkoop, M., Heijungs, R., De Schryver, A., Struijs, J. and van Zelm, R., 2013. *ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation*. *Ruimte en Milieu. Ministerie van Volkshuivesting. Ruimtelijke Ordening en Milieubeheer*.

Gould, J., Garcia-Garcia, G. and Wolf, B., 2016. Pickering Particles Prepared from Food Waste. *Materials*, 9(9), p.791.

Gov.uk, 2008. *Combined Heat and Power Incentives*. [Online] available at: <https://www.gov.uk/guidance/combined-heat-and-power-incentives> [Accessed Feb. 2017].

Gov.uk, 2014a. *Classify different types of waste*. [Online] available at: <https://www.gov.uk/how-to-classify-different-types-of-waste> [Accessed Apr. 2015].

Gov.uk, 2014b. *Guidance for the animal by-product industry*. [Online] available at: <https://www.gov.uk/government/collections/guidance-for-the-animal-by-product-industry> [Accessed Oct. 2015].

Gov.uk, 2014c. *How food businesses must dispose of food and former foodstuffs*. [Online] available at: <https://www.gov.uk/guidance/how-food-businesses-must-dispose-of-food-and-former-foodstuffs> [Accessed Jul. 2015].

Gov.uk, 2014d. *How to operate an animal by-product (ABP) processing facility*. [Online] available at: <https://www.gov.uk/guidance/how-to-operate-an-animal-by-product-abp-processing-facility> [Accessed Nov. 2015].

Gov.uk, 2014e. *Supplying and using animal by-products as farm animal feed*. [Online] available at: <https://www.gov.uk/guidance/supplying-and-using-animal-by-products-as-farm-animal-feed> [Accessed Nov. 2014].

Gov.uk, 2014f. *Using animal by-products at compost and biogas sites*. [Online] available at: <https://www.gov.uk/guidance/using-animal-by-products-at-compost-and-biogas-sites> [Accessed Nov. 2015].

Gov.uk, 2014g. *Using leftover milk and milk products as farm animal feed*. [Online] available at: <https://www.gov.uk/guidance/using-leftover-milk-and-milk-products-as-farm-animal-feed> [Accessed May 2015].

Gov.uk, 2015a. *Business and commercial waste*. [Online] available at: <https://www.gov.uk/managing-your-waste-an-overview> [Accessed Oct. 2016].

Gov.uk, 2015b. *Nitrate Vulnerable Zones*. [Online] available at: <https://www.gov.uk/nitrate-vulnerable-zones> [Accessed Oct. 2016].

Gov.uk, 2016. *Spirits Duty. Guidance. Licensing and approval*. [Online] available at: <https://www.gov.uk/guidance/spirits-duty> [Accessed Apr. 2017].

Gov.uk, 2017. *Environmental taxes, reliefs and schemes for businesses. 6. Landfill Tax*. [Online] available at: <https://www.gov.uk/green-taxes-and-reliefs/landfill-tax> [Accessed Feb. 2017].

Grafton, R.Q., Daugbjerg, C. and Qureshi, M.E., 2015. Towards food security by 2050. *Food Security*, pp.179–183.

Griffin, M., Sobal, J. and Lyson, T.A., 2009. An analysis of a community food waste stream. *Agriculture and Human Values*, 26(1–2), pp.67–81.

Grizzetti, B., Pretato, U., Lassaletta, L., Billen, G. and Garnier, J., 2013. The contribution of food waste to global and European nitrogen pollution. *Environmental Science and Policy*, 33, pp.186–195.

Grosso, M., Nava, C., Testori, R., Rigamonti, L. and Vigano, F., 2012. The implementation of anaerobic digestion of food waste in a highly populated urban area: an LCA evaluation. *Waste Management & Research*, 30(9), pp.78–87.

GS1, 2017a. *Global Product Category*. [Online] available at: <http://www.gs1.org/gpc/browser> [Accessed Jan. 2017].

GS1, 2017b. *United Nations Standard Products and Services Code*. [Online] available at: <http://www.unspsc.org/> [Accessed Jan. 2017].

Guendehou, G.H.S., Koch, M., Hockstad, L., Pipatti, R. and Yamada, M., 2006. Incineration and open burning of waste. In: *2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, Oers, L. van, Sleeswijk, A.W., Suh, S., Haes, H.A.U. de, Bruijn, H. de, Duin, R. van, Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., Ven, B.L. van der and Weidema, B.P., 2004. *Handbook on Life Cycle Assessment*. New York, Boston, Dordrecht, London, Moscow: Kluwer Academic Publishers.

Guinee, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T. and Rydberg, T., 2010. Life Cycle Assessment: Past, Present, and Future. *Environmental Science & Technology*, 45, pp.90–96.

Haight, M., 2005. Assessing the environmental burdens of anaerobic digestion in comparison to alternative options for managing the biodegradable fraction of municipal solid wastes. *Water Science and Technology*, 52(1–2), pp.553–559.

Hanandeh, A. El and El-Zein, A., 2010. Life-cycle assessment of municipal solid waste management alternatives with consideration of uncertainty: SIWMS development and application. *Waste Management*, 30(5), pp.902–911.

Hannah Dick, Hennig, A. and Scholes, P., 2016. *Comparing the cost of alternative waste treatment options. Gate fees report 2015/16*. WRAP, September.

Harrison, K.W., Dumas, R.D., Solano, E., Barlaz, M.A., Downey Brill, E.J. and Ranjithan, S.R., 2001. Decision support tool for life-cycle-based solid waste management. *Journal of Computing in Civil Engineering*, 15(1), pp.44–58.

Hauschild, M. and Barlaz, M., 2009. LCA in waste management—introduction to principle and method. In: T. Christensen, ed., *Solid waste technology and management*. Oxford: Wiley-Blackwell Publishing Ltd.

Hauschild, M. and Potting, J., 2005. Spatial Differentiation in Life Cycle impact assessment - The EDIP2003 methodology. *Environmental news*, 80.

Heinzerling, L. and Ackerman, F., 2002. *Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection*. [Online] available at: <http://www.ase.tufts.edu/gdae/publications/C-B%20pamphlet%20final.pdf> [Accessed Nov. 2016]. Washington DC (USA).

Herva, M. and Roca, E., 2013. Ranking municipal solid waste treatment alternatives based on ecological footprint and multi-criteria analysis. *Ecological Indicators*, 25, pp.77–84.

Hidalgo, D., Martín-Marroquín, J.M. and Nieto, P., 2016. Anaerobic co-digestion of agro-food waste mixtures in a fed-batch basis. *Environmental Technology*, pp.1–9.

Hill, S., 2014. *Waste not, want not - Reducing livestock's greenhouse gas emissions in the UK.* [Online] available at: <http://www.fcrn.org.uk/sites/default/files/141122_waste_not_want_not_final.pdf> [Accessed Feb. 2015] 24 November.

Himanen, M. and Hänninen, K., 2009. Effect of commercial mineral-based additives on composting and compost quality. *Waste Management*, 29(8), pp.2265–2273.

Hla, S.S. and Roberts, D., 2015. Characterisation of chemical composition and energy content of green waste and municipal solid waste from Greater Brisbane, Australia. *Waste Management*, 41, pp.12–19.

HM Revenue & Customs, 2014. *Landfill Tax - Liability of waste 'fines'. Consultation document*. 30 June.

Ho, W.S., Hashim, H., Lim, J.S., Lee, C.T., Sam, K.C. and Tan, S.T., 2017. Waste Management Pinch Analysis (WAMPA): Application of Pinch Analysis for greenhouse gas (GHG) emission reduction in municipal solid waste management. *Applied Energy*, 185, pp.8–10.

Hodge, K.L., Levis, J.W., Decarolis, J.F. and Barlaz, M.A., 2016. A Systematic Evaluation of Industrial, Commercial, and Institutional Food Waste Management Strategies in the United States. *Environmental Science & Technology*, 50, pp.8444–8452.

Hokkanen, J. and Salminen, P., 1997. Choosing a solid waste management system using multicriteria decision analysis. *European Journal of Operational Research*, 98(1), pp.19–36.

Hokkanen, J., Salminen, P., Rossi, E. and Ettala, M., 1995. The choice of a solid waste management system using the Electre II decision-aid method. *Waste Management & Research*, 13(2), pp.175–193.

Hollandtrade.com, 2015. *Holland is world-leading exporter of agri-food products*. [Online] available at: <http://www.hollandtrade.com/sector-information/agriculture-and-food/?bstnum=4909> [Accessed May 2016].

Hoornweg, D. and Bhada-Tata, P., 2012. What a waste. A Global Review of Solid Waste Management. *Urban Development Series Knowledge Papers*, March, No. 15.

Horizon 2020 Framework Programme of the European Union, 2017. *REFRESH: Resource Efficient Food and dRink for the Entire Supply cHain*. [Online] available at: <http://eu-refresh.org/> [Accessed Jan. 2017].

Huang, I.B., Keisler, J. and Linkov, I., 2011. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of the Total Environment*, 409(19), pp.3578–3594.

Hung, M.L., Ma, H.W. and Yang, W.F., 2007. A novel sustainable decision making model for municipal solid waste management. *Waste Management*, 27(2), pp.209–219.

Hung, M.L., Yang, W.F., Ma, H.W. and Yang, Y.M., 2006. A novel multiobjective programming approach dealing with qualitative and quantitative objectives for environmental management. *Ecological Economics*, 56(4), pp.584–593.

Institute of Grocery Distribution (IGD), 2014a. *Composting*. [Online] available at: <http://www.igd.com/our-expertise/Supply-chain/WastePrevention/15923/Composting/> [Accessed Oct. 2015].

Institute of Grocery Distribution (IGD), 2014b. *The ECR UK waste hierarchy*. [Online] available at: <http://www.igd.com/our-expertise/Supply-chain/WastePrevention/16275/The-ECR-UK-Waste-Hierarchy/> [Accessed Oct. 2014].

Institute of Grocery Distribution (IGD), 2014c. *The 'Six-to-Fix' to prevent waste*. [Online] available at: <http://www.igd.com/Research/Supply-chain/Waste-Prevention/Six-to-fix-to-prevent-waste/> [Accessed Oct. 2014].

Institute of Mechanical Engineers, 2013. *Global Food - Waste Not, Want Not*. London (UK). [Online] available at: <http://www.imeche.org/docs/default-source/reports/Global_Food_Report.pdf?sfvrsn=0> [Accessed May 2014].

International Records Management Trust (IRMT), 2006. Project management guideline. Appendix D – Cost/Benefit Analysis Guide. *ITRM Guideline CPM 110-01*. 23 January, London (UK).

Ipek, U., Arslan, E.I., Öbek, E., Karataş, F. and Erulaş, F.A., 2005. Determination of vitamin losses and degradation kinetics during composting. *Process Biochemistry*, 40(2), pp.621–624.

Irani, Z. and Sharif, A.M., 2016. Sustainable food security futures. Perspectives on food waste and information across the food supply chain. *Journal of Enterprise Information Management*, 29(2), pp.171–178.

ISO, 2006a. *ISO 14040:2006. Environmental management -- Life cycle assessment -- Principles and framework*. [Online] available at: <https://www.iso.org/standard/37456.html> [Accessed Mar. 2017].

ISO, 2006b. *ISO 14044:2006. Preview Environmental management -- Life cycle assessment -- Requirements and guidelines*. [Online] available at: <https://www.iso.org/standard/38498.html> [Accessed Mar. 2017].

Jamasb, T. and Nepal, R., 2010. Issues and options in waste management: A social cost-benefit analysis of waste-to-energy in the UK. *Resources, Conservation and Recycling*, 54(12), pp.1341–1352.

Joint FAO/WHO Food Standards Programme, 2016. Proposed draft revision of the general standard for the labelling of prepackaged foods: date marking. *Codex Committee on Food Labelling*, 9–13 May, pp.1–28.

Karagiannidis, A. and Moussiopoulos, N., 1997. Application of ELECTRE III for the integrated management of municipal solid wastes in the Greater Athens Area. *European Journal of Operational Research*, 97(96), pp.439–449.

Karmee, S.K., 2016. Liquid biofuels from food waste: Current trends, prospect and limitation. *Renewable and Sustainable Energy Reviews*, 53, pp.945–953.

Karmperis, A.C., Aravossis, K., Tatsiopoulos, I.P. and Sotirchos, A., 2013. Decision support models for solid waste management: Review and game-theoretic approaches. *Waste Management*, 33(5), pp.1290–1301.

Kaufman, S.M., Krishnan, N. and Themelis, N.J., 2010. A screening life cycle metric to benchmark the environmental sustainability of waste management systems. *Environmental Science and Technology*, 44(15), pp.5949–5955.

Khalid, A., Arshad, M., Anjum, M., Mahmood, T. and Dawson, L., 2011. The anaerobic digestion of solid organic waste. *Waste Management*, 31(8), pp.1737–1744.

Khan, M.M.-U.-H., Jain, S., Vaezi, M. and Kumar, A., 2015. Development of a decision model for the techno-economic assessment of municipal solid waste utilization pathways. *Waste Management*, 48, pp. 548-564.

Khoo, H.H., Lim, T.Z. and Tan, R.B.H., 2010. Food waste conversion options in Singapore: Environmental impacts based on an LCA perspective. *Science of the Total Environment*, 408(6), pp.1367–1373.

Kijak, R. and Moy, D., 2004. A decision support framework for sustainable waste management. *Journal of Industrial Ecology*, 8(3), pp.33–50.

Kim, G., Park, C.S. and Yoon, K.P., 1997. Identifying investment opportunities for advanced manufacturing systems with comparative-integrated performance measurement.

International Journal of Production Economics, 50(1), pp.23–33.

Kim, J., Goldsmith, P. and Thomas, M.H., 2010. Economic impact and public costs of confined animal feeding operations at the parcel level of Craven County, North Carolina. *Agriculture and Human Values*, 27(1), pp.29–42.

Kim, M.-H. and Kim, J.-W., 2010. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. *Science of the total environment*, 408(19), pp.3998–4006.

Kloepffer, W., 2008. Life Cycle Sustainability Assessment of Products. *International Journal Life Cycle Assessment*, 13(2), pp.89–95.

Klöpffer, W., 2003. Life-cycle based methods for sustainable product development. *International Journal of Life Cycle Assessment*, 8(3), pp.157–159.

Komilis, D. and Ferrer, A.S., 2017. Life cycle assessment in solid waste management: Facts and artefacts. *Waste Management*, 61, pp.1–2.

Kondusamy, D. and Kalamdhad, A.S., 2014. Pre-treatment and anaerobic digestion of food waste for high rate methane production – A review. *Journal of Environmental Chemical Engineering*, 2(3), pp.1821–1830.

Kothari, C., 2004. *Research methodology: methods and techniques*. Second rev ed. *New Age International*. New Age International Publishers.

Kumar, P., Hussain, A. and Dubey, S.K., 2015. Methane formation from food waste by anaerobic digestion. *Biomass Conversion and Biorefinery*, September, pp.1–10.

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O. and Ward, P.J., 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of the Total Environment*, 438, pp.477–489.

Kwak, T.H., Maken, S., Lee, S., Park, J.W., Min, B. ryul and Yoo, Y.D., 2006. Environmental aspects of gasification of Korean municipal solid waste in a pilot plant. *Fuel*, 85, pp.2012–2017.

Kwon, S.H. and Lee, D.H., 2004. Evaluation of Korean food waste composting with fed-batch operations I: Using water extractable total organic carbon contents (TOCw). *Process Biochemistry*, 39(10), pp.1183–1194.

Kythreotou, N., Florides, G. and Tassou, S. a., 2014. A review of simple to scientific models for anaerobic digestion. *Renewable Energy*, 71, pp.701–714.

Lasaridi, K.E. and Stentiford, E.I., 1998. A simple respirometric technique for assessing compost stability. *Water Research*, 32(12), pp.3717–3723.

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z. and Christensen, T.H., 2014a. Review of LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. *Waste Management*, 34(3), pp.573–588.

Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen, T.H. and Hauschild, M.Z., 2014b. Review of LCA studies of solid waste management systems - Part II: Methodological guidance for a better practice. *Waste Management*, 34(3), pp.589–606.

Lebersorger, S. and Schneider, F., 2011. Discussion on the methodology for determining food waste in household waste composition studies. *Waste Management*, 31, pp.1924–33.

Lee, C.K.M., Yeung, C.L., Xiong, Z.R. and Chung, S.H., 2016. A mathematical model for municipal solid waste management - A case study in Hong Kong. *Waste Management*, 58, pp.430–441.

Lee, P. and Willis, P., 2010. *Waste arisings in the supply of food and drink to households in the UK. Final Report*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/Waste%20arisings%20in%20the%20supply%20of%20food%20and%20drink%20toUK%20households,%20Nov%202011.pdf> [Accessed Nov. 2014], Oakdene Hollins & WRAP, March.

Lee, S.-H., Choi, K.-I., Osako, M. and Dong, J.-I., 2007. Evaluation of environmental burdens caused by changes of food waste management systems in Seoul, Korea. *The Science of the Total Environment*, 387(1–3), pp.42–53.

Legislation.gov.uk, 2003. Waste and Emissions Trading Act 2003. Chapter 33. [Online] available at: <http://www.legislation.gov.uk/ukpga/2003/33/pdfs/ukpga_20030033_en.pdf?section-32-7-b-ii> [Accessed Oct. 2014].

Leung, D.Y.C. and Wang, J., 2016. An overview on biogas generation from anaerobic digestion of food waste. *International Journal of Green Energy*, 13(2), pp.119–131.

Levén, L., Nyberg, K. and Schnürer, A., 2012. Conversion of phenols during anaerobic digestion of organic solid waste - A review of important microorganisms and impact of temperature. *Journal of Environmental Management*, 95(SUPPL.), pp.S99–S103.

Levis, J.W., Barlaz, M.A., DeCarolis, J.F. and Ranjithan, S.R., 2013. A generalized multistage optimization modeling framework for life cycle assessment-based integrated solid waste management. *Environmental Modelling and Software*, 50, pp.51–65.

Li, Z., Huang, G., Yu, H., Zhou, Y. and Huang, W., 2015. Critical factors and their effects on product maturity in food waste composting. *Environmental Monitoring and Assessment*, 187(4), p.217.

Liamsanguan, C. and Gheewala, S.H., 2008. LCA: A decision support tool for environmental assessment of MSW management systems. *Journal of Environmental Management*, 87(1), pp.132–138.

Lin, C., Pfaltzgraff, L.A., Herrero-Davila, L., Mubofu, E.B., Solhy, A., Clark, P.J., Koutinas, A., Kopsahelis, N., Stamatelatou, K., Dickson, F., Thankappan, S., Zahouily, M., Brocklesby, R. and Luque, R., 2013. Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. *Energy & Environmental Science*, 6, pp.426–464.

Lin, C.S.K., Koutinas, A.A., Stamatelatou, K., Mubofu, E.B., Matharu, A.S., Kopsahelis, N., Pfaltzgraff, L.A., Clark, J.H., Papanikolaou, S., Kwan, T.H. and Luque, R., 2014. Current and future trends in food waste valorization for the production of chemicals, materials and fuels: a global perspective. *Biofuels, Bioproducts and Biorefining*, 8, pp.686–715.

Lipinski, B., Hanson, C., Lomax, J., Kitinoja, L., Waite, R. and Searchinger, T., 2013. *Reducing Food Loss and Waste. Working paper*. *Installment 2 of 'Creating a Sustainable Food Future'*, [Online] available at: <http://unep.org/wed/docs/WRI-UNEP-Reducing-Food-Loss-and-Waste.pdf> [Accessed Jan. 2014], World Resources Institute, Washington DC (USA).

Lipinski, B., O'Connor, C. and Hanson, C., 2016. *SDG target 12.3 on food loss and waste: 2016 progress report*. Champions 12.3, September.

Lohri, C.R., Sweeney, D. and Rajabu, H.M., 2015. Carbonizing urban biowaste for low-cost char production in developing countries - A review of knowledge, practices and technologies. Eawag, MIT D-Lab, UDSM.

Lundie, S. and Peters, G.M., 2005. Life cycle assessment of food waste management options. *Journal of Cleaner Production*, 13(3), pp.275–286.

Malamis, D., Moustakas, K., Bourka, A., Valta, K., Papadaskalopoulou, C., Panaretou, V., Skiadi, O. and Sotiropoulos, A., 2015. Compositional analysis of biowaste from study sites in Greek municipalities. *Waste and Biomass Valorization*, 6(5), pp.637–646.

Manfredi, S. and Cristobal, J., 2016. Towards more sustainable management of European food waste: Methodological approach and numerical application. *Waste Management and Research*, 34(9), pp.957–968.

Mao, C., Feng, Y., Wang, X. and Ren, G., 2015. Review on research achievements of biogas from anaerobic digestion. *Renewable and Sustainable Energy Reviews*, 45, pp.540–555.

Marsland, T. and Whiteley, B., 2015. *Hazards from landspreading wastes. Methodology for Rapid Evidence Assessment*.

Martinez-Sanchez, V., Kromann, M.A. and Astrup, T.F., 2015. Life cycle costing of waste management systems: Overview, calculation principles and case studies. *Waste Management*, 36, pp.343–355.

Martinez-Sanchez, V., Tonini, D., Møller, F. and Astrup, T.F., 2016. Life-Cycle Costing of Food Waste Management in Denmark: Importance of indirect effects. *Environmental Science & Technology*, 50, p.4513−4523.

Matharu, A.S., de Melo, E.M. and Houghton, J.A., 2016. Opportunity for high value-added chemicals from food supply chain wastes. *Bioresource Technology*, 215, pp.123–130.

Matsuda, T., Yano, J., Hirai, Y. and Sakai, S., 2012. Life-cycle greenhouse gas inventory analysis of household waste management and food waste reduction activities in Kyoto, Japan. *The International Journal of Life Cycle Assessment*, 17(6), pp.743–752.

Meeker, D.L., 2006. *Essential rendering. All about the animal by-products industry*. ISBN: 0-9654660-3-5.

Mena, C., Adenso-Diaz, B. and Yurt, O., 2011. The causes of food waste in the supplier-retailer interface: Evidences from the UK and Spain. *Resources, Conservation and Recycling*, 55(6), pp.648–658.

Min, H., 1994. International Supplier Selection: A Multi-attribute Utility Approach. *International Journal of Physical Distribution & Logistics Management*, 24(5), pp.24–33.

Ministry of Housing, Spatial Planning and the Environment (The Netherlands), 2000. *Eco-indicator 99. Manual for Designers. A damage oriented method for Life Cycle Impact Assessment*. The Hague (The Netherlands).

Mirabella, N., Castellani, V. and Sala, S., 2014. Current options for the valorization of food manufacturing waste: A review. *Journal of Cleaner Production*, 65, pp.28–41.

Mishan, E.J. and Quah, E., 2007. Introductory remarks. In: *Cost-Benefit Analysis*, 5th edition. Oxon (UK): Routledge. Taylor & Francis Group, p.3.

Møller, J., Boldrin, A. and Christensen, T.H., 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. *Waste Management & Research*, 27(8), pp.813–824.

Morawicki, R.O., 2012. *Handbook of sustainability for the food sciences*. Chichester (UK): Wiley-Blackwell.

Morrissey, A.J. and Browne, J., 2004. Waste management models and their application to sustainable waste management. *Waste Management*, 24(3), pp.297–308.

Morton, C., 2015. *Anaerobic Digestion In The UK — 2015 Update*. [Online] available at: <http://www.biocycle.net/2015/05/13/anaerobic-digestion-in-the-uk-2015-update/> [Accessed May 2016].

Münster, M., Ravn, H., Hedegaard, K., Juul, N. and Ljunggren Söderman, M., 2015. Economic and environmental optimization of waste treatment. *Waste Management*, 38, pp.486–495.

Mussatto, S.I., Dragone, G. and Roberto, I.C., 2006. Brewers' spent grain: Generation, characteristics and potential applications. *Journal of Cereal Science*, 43(1), pp.1–14.

Myerson, R.B., 1991. *Game Theory: Analysis of Conflict*. 1997 ed. Cambridge, MA: Harvard University Press. ISBN: 0674341163.

Nakasaki, K., Mimoto, H., Tran, Q.N.M. and Oinuma, A., 2015. Composting of food waste subjected to hydrothermal pretreatment and inoculated with Paecilomyces sp. FA13. *Bioresource Technology*, 180, pp.40–46.

Ness, B., Urbel-Piirsalu, E., Anderberg, S. and Olsson, L., 2007. Categorising tools for sustainability assessment. *Ecological Economics*, 60(3), pp.498–508.

Nordic Council of Ministers, 2007. *Nordic Guidline for Cost-Benefit Analysis in Waste Management*. Copenhagen (Denmark). ISBN: 978-92-893-1555-5.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E. and Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. *Journal of Cleaner Production*, 140, pp.399–409.

O'Connor, C., Gheoldus, M. and Jan, O., 2014. *Comparative Study on EU Member States' legislation and practices on food donation, Final report*. [Online] available at: <http://www.eesc.europa.eu/resources/docs/comparative-study-on-eu-member-states-legislation-and-practices-on-food-donation_finalreport_010714.pdf> [Accessed Apr. 2015], June.

Oakdene Hollins, Responsible Hospitality Partnership and WRAP, 2013. *Overview of Waste in the UK Hospitality and Food Service Sector*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/Overview%20of%20Waste%20in%20the%20UK%20Hospitality%20and%20Food%20Service%20Sector%20FINAL.pdf> [Accessed Jan. 2015].

OECD, 2015. *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development*. ISBN: 978-92-6423880-0.

Okoro, O.V., Sun, Z. and Birch, J., 2016. Meat processing waste as a potential feedstock for biochemicals and biofuels – A review of possible conversion technologies. *Journal of Cleaner Production*, 142, pp.1583–1608.

Opatokun, S.A., Prabhu, A., Al Shoaibi, A., Srinivasakannan, C. and Strezov, V., 2017. Food wastes derived adsorbents for carbon dioxide and benzene gas sorption. *Chemosphere*, 168, pp.326–332.

Opatokun, S.A., Strezov, V. and Kan, T., 2015. Product based evaluation of pyrolysis of food waste and its digestate. *Energy*, 92, pp.349–354.

Opricovic, S. and Tzeng, G.H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research*, 156(2), pp.445–455.

Ortner, M., Drosg, B., Stoyanova, E. and Bochman, G., 2013. Industrial residues for biomethane production. In: N.E. Korres, P. O'Kiley, J.A.H. Benzie and J.S. West, eds., *Bioenergy production by anaerobic digestion. Using agricultural biomass and organic wastes*. Earthscan, pp.111–135.

Panepinto, D., Blengini, G. a. and Genon, G., 2015. Economic and environmental comparison between two scenarios of waste management: MBT vs thermal treatment. *Resources, Conservation and Recycling*, 97, pp.16–23.

Papargyropoulou, E., Lozano, R., K. Steinberger, J., Wright, N. and Ujang, Z. Bin, 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production*, 76, pp.106–115.

Parfitt, J. and Parry, A., 2016. *Food surplus and waste in UK wholesale grocery, 2015. Research note*. WRAP, November.

Parfitt, J., Stanley, C. and Thompson, L., 2016. *Guidance for food and drink manufacturers and retailers on the use of food surplus as animal feed*. *Version 1.0*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/2016%2005%2017%20Animal%20Feed%20Guidance%20v1.0%20for%20publication.pdf> [Accessed Jun. 2016], WRAP, May.

Parfitt, Woodham, S., Swan, E., Castella, T. and Parry, A., 2016. *Quantification of food surplus, waste and related materials in the grocery supply chain. Final report - v2*. WRAP, May. ISBN: 978-1-84405-473-2.

Parliament of the United Kingdom, 2008. *Climate Change Act 2008*. *HM Government*. [Online] available at: <http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf> [Accessed May 2015].

Pearce, D., Atkinson, G. and Mourato, S., 2006. *Cost-Benefit Analysis and the Environment: Recent Developments*. OECD. ISBN: 92-64-01004-1.

Peigne, J. and Girardin, P., 2004. Environmental impacts of farm-scale composting practices. *Water, Air, and Soil Pollution*, 153, pp.45–68.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T. and Rebitzer, G., 2004. Life cycle assessment Part 2: Current impact assessment practice. *Environment International*, 30(5), pp.721–739.

Pham, T.P.T., Kaushik, R., Parshetti, G.K., Mahmood, R. and Balasubramanian, R., 2014. Food waste-to-energy conversion technologies: Current status and future directions.

Waste Management, 38, pp.399–408.

Pilavachi, P.A., Chatzipanagi, A.I. and Spyropoulou, A.I., 2009. Evaluation of hydrogen production methods using the Analytic Hierarchy Process. *International Journal of Hydrogen Energy*, 34(13), pp.5294–5303.

Pires, A., Martinho, G. and Chang, N.-B., 2011. Solid waste management in European countries: A review of systems analysis techniques. *Journal of Environmental Management*, 92(4), pp.1033–1050.

Pirlot, M., 1997. A Common Framework for Describing Some Outranking Methods. *Journal of Multi-Criteria Decision Analysis*, 6(2), pp.86–92.

Pleissner, D., Qi, Q., Gao, C., Rivero, C.P., Webb, C., Lin, C.S.K. and Venus, J., 2016. Valorization of organic residues for the production of added value chemicals: A contribution to the bio-based economy. *Biochemical Engineering Journal*, 116, pp.3–16.

Pohekar, S.D. and Ramachandran, M., 2004. Application of multi-criteria decision making to sustainable energy planning - A review. *Renewable and Sustainable Energy Reviews*, 8(4), pp.365–381.

Porter, S.D., Reay, D.S., Higgins, P. and Bomberg, E., 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. *Science of The Total Environment*, 571, pp.721–729.

Pré Consultants, 2016. *SimaPro Database Manual. Methods library*. [Online] available at: <https://www.pre-sustainability.com/download/DatabaseManualMethods.pdf> [Accessed May 2016], Version 2.9. April.

Priefer, C., Jörissen, J. and Bräutigam, K.-R., 2016. Food waste prevention in Europe – A cause-driven approach to identify the most relevant leverage points for action. *Resources, Conservation and Recycling*, 109, pp.155–165.

Priestley, S., 2016. *Food Waste. Briefing Paper Number CBP07552*. August.

Quested, T., Ingle, R. and Parry, A., 2013. *Household Food and Drink Waste in the United Kingdom 2012. Final report*. WRAP, November. ISBN: 978-1-84405-458-9.

Quested, T. and Johnson, H., 2009. *Household Food and Drink Waste in the UK*. WRAP, November. ISBN: 1-84405-430-6.

Quested, T. and Murphy, L., 2014. *Household food and drink waste: A product focus. Final Report*. WRAP. ISBN: 978-1-84405-469-5.

Quested, T. and Parry, A., 2011. *New estimates for household food and drink waste in the UK. Final report (version 1.1)*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/New%20estimates%20for%20household%20food%20and%20drink%20waste%20in%20the%20UK%20FINAL%20v2%20(updated%207thAugust2012).pdf> [Accessed Feb. 2015], WRAP, November.

Quested, T. and Parry, A., 2017. *Household Food Waste in the UK, 2015. Final report*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/Household_food_waste_in_the_UK_2015_Report.pdf> [Accessed Jan. 2017], WRAP, January.

Raak, N., Symmank, C., Zahn, S., Aschemann-Witzel, J. and Rohm, H., 2016. Processing- and product-related causes for food waste and implications for the food supply chain.

Waste Management, 61, pp.461–472.

Ramzan, N., Ashraf, A., Naveed, S. and Malik, A., 2011. Simulation of hybrid biomass gasification using Aspen plus: A comparative performance analysis for food, municipal solid and poultry waste. *Biomass and Bioenergy*, 35(9), pp.3962–3969.

Ravindran, R. and Jaiswal, A.K., 2015. Exploitation of food industry waste for high-value products. *Trends in Biotechnology*, 34(1), pp.58–69.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P. and Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30(5), pp.701–720.

Reich, M.C., 2005. Economic assessment of municipal waste management systems - Case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *Journal of Cleaner Production*, 13(3), pp.253–263.

Reynolds, C., Piantadosi, J. and Boland, J., 2015. Rescuing Food from the Organics Waste Stream to Feed the Food Insecure: An Economic and Environmental Assessment of Australian Food Rescue Operations Using Environmentally Extended Waste Input-Output Analysis. *Sustainability*, 7(4), pp.4707–4726.

Rigamonti, L., Sterpi, I. and Grosso, M., 2016. Integrated municipal waste management systems: An indicator to assess their environmental and economic sustainability. *Ecological Indicators*, 60, pp.1–7.

Roghanian, E., Sheykhan, A. and Sayyad Abendankashi, E., 2014. An application of fuzzy TOPSIS to improve the process of supply chain management in the food industries: A case study of protein products manufacturing company. *Decision Science Letters*, 3(1), pp.17–26.

Rossi, V., Cleeve-Edwards, N., Lundquist, L., Schenker, U., Dubois, C., Humbert, S. and Jolliet, O., 2015. Life cycle assessment of end-of-life options for two biodegradable packaging materials: Sound application of the European waste hierarchy. *Journal of Cleaner Production*, 86, pp.132–145.

Rothenberger, S., Zurbrügg, C., Enayetullah, I. and Sinha, A. H.M.M., 2006. *Decentralised Composting for Cities of Low- and Middle- Income Countries*. Waste Concern.

Ruggieri, L., Cadena, E., Martínez-Blanco, J., Gasol, C.M., Rieradevall, J., Gabarrell, X., Gea, T., Sort, X. and Sánchez, A., 2009. Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analyses of the composting process. *Journal of Cleaner Production*, 17(9), pp.830–838.

Ruiter, H. de, Macdiamid, J.I., Matthews, R.B., Kastner, T. and Smith, P., 2015. Global cropland and greenhouse gas impacts of UK food supply are increasingly located overseas. *Journal of The Royal Society Interface*, 13(114).

Russ, W. and Meyer-Pittroff, R., 2004. Utilizing waste products from the food production and processing industries. *Critical reviews in food science and nutrition*, 44(1), pp.57–62.

Salemdeeb, R., zu Ermgassen, E.K.H.J., Kim, M.H., Balmford, A. and Al-Tabbaa, A., 2017. Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. *Journal of Cleaner Production*, 140, pp.871–880.

San Martin, D., Ramos, S. and Zufía, J., 2015. Valorisation of food waste to produce new raw materials for animal feed. *Food Chemistry*, 198, pp. 68-74.

Sander, K., Schilling, S. and Lüskow, H., 2008. *Review of the European List of Waste. Final report*. [Online] available at: <http://ec.europa.eu/environment/waste/pdf/low_review_oekopol.pdf> [Accessed Jan. 2015], November.

Santos, M., Jiménez, J.J., Bartolomé, B., Gómez-Cordovés, C. and Del Nozal, M.J., 2003. Variability of brewer's spent grain within a brewery. *Food Chemistry*, 80(1), pp.17–21.

SAVE FOOD, 2016. *Global Initiative on Food Loss and Waste Reduction. Key facts on food loss and waste you should know!* [Online] available at: <http://www.fao.org/save-food/resources/keyfindings/en/> [Accessed Feb. 2017]. Food and Agriculture Organization of the United Nations (FAO), Messe Düsseldorf.

Schaub, S.M. and Leonard, J.J., 1996. Composting: An alternative waste management option for food processing industries. *Trends in Food Science and Technology*, 7(8), pp.263–268.

Scientific Applications International Corporation (SAIC), 2006. *Life Cycle Assessment: Principles and Practice*. [Online] available at: <http://medcontent.metapress.com/index/A65RM03P4874243N.pdf> [Accessed Feb. 2016], May.

Segrè, A., Falasconi, L., Politano, A. and Vittuari, M., 2014. *Background paper on the economics of food loss and waste (unedited working paper)*. Rome (Italy).

Sen, B., Aravind, J., Kanmani, P. and Lay, C.-H., 2016. State of the art and future concept of food waste fermentation to bioenergy. *Renewable and Sustainable Energy Reviews*, 53, pp.547–557.

Sevigné-Itoiz, E., Gasol, C.M., Rieradevall, J. and Gabarrell, X., 2015. Methodology of supporting decision-making of waste management with material flow analysis (MFA) and consequential life cycle assessment (CLCA): Case study of waste paper recycling. *Journal of Cleaner Production*, 105, pp.253–262.

Shih, H.S., Shyur, H.J. and Lee, E.S., 2007. An extension of TOPSIS for group decision making. *Mathematical and Computer Modelling*, 45(7–8), pp.801–813.

Skeer, J. and Nakada, S., 2016. Potential for Biomass and Biofuel through Sustainable Intensification of Agriculture and Reduction of Food Losses and Wastec. *Natural Resources*, 7, pp.23–27.

Smil, V., 2004. Improving Efficiency and Reducing Waste in Our Food System. *Environmental Sciences*, 1(1), pp.17–26.

Soltani, A., Sadiq, R. and Hewage, K., 2016. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making. *Journal of Cleaner Production*, 113, pp.388–399.

Statutory Instruments, 2011. *The Waste (England and Wales) Regulations 2011*. No. 988.

Statutory Instruments, 2014. *The Food Information Regulations 2014.* No. 1855.

Stefanović, G., Milutinović, B., Vučićević, B., Denčić-Mihajlov, K. and Turanjanin, V., 2016. A comparison of the Analytic Hierarchy Process and the Analysis and Synthesis of

Parameters under Information Deficiency method for assessing the sustainability of waste management scenarios. *Journal of Cleaner Production*, 130, pp. 155-165.

Stuart, T., 2009. *Waste, uncovering the global food scandal*. London (UK): Penguin. ISBN: 0141036346.

Stuart, T., Miers, T. and Wahaca, n.d. *The pig idea*. [Online] available at: <http://thepigidea.org/> [Accessed May 2016].

Styles, D., Dominguez, E.M. and Chadwick, D., 2016. Environmental balance of the of the UK biogas sector: An evaluation by consequential life cycle assessment. *Science of the Total Environment*, 560–561, pp.241–253.

Su, J.-P., Hung, M.-L., Chao, C.-W. and Ma, H., 2010. Applying multi-criteria decision-making to improve the waste reduction policy in Taiwan. *Waste Management & Research*, 28(1), pp.20–8.

Sugiura, K., Yamatani, S., Watahara, M. and Onodera, T., 2009. Ecofeed, animal feed produced from recycled food waste. *Veterinaria italiana*, 45(3), pp.397–404.

Suler, D.J. and Finstein, M.S., 1977. Effect of temperature, aeration, and moisture on CO2 formation in bench scale, continuously thermophilic composting of solid waste. *Applied and Environmental Microbiology*, 33(2), pp.345–350.

Suwannarat, J. and Ritchie, R.J., 2015. Anaerobic digestion of food waste using yeast. *Waste Management*, 42, pp.61–66.

Tagliaferri, C., Evangelisti, S., Clift, R., Lettieri, P., Chapman, C. and Taylor, R., 2016. Life cycle assessment of conventional and advanced two-stage energy-from-waste technologies for methane production. *Journal of Cleaner Production*, 129, pp.144–158.

Tampio, E., Marttinen, S. and Rintala, J., 2016. Liquid fertilizer products from anaerobic digestion of food waste: mass, nutrient and energy balance of four digestate liquid treatment systems. *Journal of Cleaner Production*, 125, pp.22–32.

Tan, S.T., Lee, C.T., Hashim, H., Ho, W.S. and Lim, J.S., 2014. Optimal process network for municipal solid waste management in Iskandar Malaysia. *Journal of Cleaner Production*, 71, pp.48–58.

The Commission of the European Communities, 2005. Commission Regulation (EC) No. 2073/2005 of 15 November 2005 on microbiological criteria for foodstuffs. *Official Journal of the European Communitites*, L 338, pp.1–26.

The Commission of the European Communities, 2006. Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs. *Official Journal of the European Communitites*, L 364, pp.5–24.

The Council of the European Communities, 1975. Council Directive of 15 December 1975 on waste (75/442/EEC). *Official Journal of the European Communities*, July, p.L 194/39-41.

The Council of the European Union, 1999. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. *Official Journal of the European Communities*, July, p.L 182/1-19.

The Council of the European Union, 2006. Council Directive 2006/112/EC of 28 November 2006. *Official Journal of the European Union*, November, p.L 347/1-118.

The European Parliament and the Council of the European Union, 2002. *Regulation (EC) No*

178/2002 of the European Parliament and of the Council of 28 January 2002. *Official Journal of the European Communities*.

The European Parliament and the Council of the European Union, 2003. Regulation (EC) No 1831/2003 of the European Parliament and of the Council of 22 September 2003. *Official Journal of the European Union*, October, p.L 268/29-42.

The European Parliament and the Council of the European Union, 2004a. Corrigendum to Directive 2004/41/EC of the European Parliament and of the Council of 21 April 2004 repealing certain directives concerning food hygiene and health conditions for the production and placing on the market of certain products of animal origin. *Official Journal of the European Union*, June, p.L 195/12-15.

The European Parliament and the Council of the European Union, 2004b. Corrigendum to Regulation (EC) No 852/2004 of the European Parliament and of the Council of 29 April 2004 on the hygiene of foodstuffs. *Official Journal of the European Union*, June, p.L 226/3-21.

The European Parliament and the Council of the European Union, 2004c. Corrigendum to Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for food of animal origin. *Official Journal of the European Union*, June, p.L 226/22-82.

The European Parliament and the Council of the European Union, 2004d. Corrigendum to Regulation (EC) No 854/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific rules for the organisation of official controls on products of animal origin intended for human consumption. *Official Journal of the European Union*, June, p.L 226/83-127.

The European Parliament and the Council of the European Union, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008. *Official Journal of the European Union*, November, p.L 312/3-30.

The European Parliament and the Council of the European Union, 2009a. Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009. *Official Journal of the European Union*, p.L 300/1-33.

The European Parliament and the Council of the European Union, 2009b. Regulation (EC) No 767/2009 of the European Parliament and of the Council of 13 July 2009. *Official Journal of the European Union*, September, p.L 229/1-28.

The European Parliament and the Council of the European Union, 2010. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast). *Official Journal of the European Union*, L334, pp.17–119.

The European Parliament and the Council of the European Union, 2011. Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011. *Official Journal of the European Union*, November, p.L 304/18-63.

The Guardian, 2015. *'It's like eating a hedgerow': why do hop shoots cost €1,000 a kilo?* [Online] available at: <http://www.theguardian.com/lifeandstyle/wordofmouth/2015/may/18/its-like-eating-a-hedgerow-why-do-hop-shoots-cost-1000-a-kilo> [Accessed May 2015].

The Secretary of State, 2010a. *The Air Quality Standards Regulations 2010*. No. 1001.

The Secretary of State, 2010b. The Animal Feed (England) Regulations 2010. *Statutory Instruments*. No. 2503.

The Secretary of State, 2013. The Animal By-Products (Enforcement) (England) Regulations 2013. *Statutory Instruments*. No. 2952.

Thi, N.B.D., Kumar, G. and Lin, C.-Y., 2015. An overview of food waste management in developing countries: Current status and future perspective. *Journal of Environmental Management*, 157, pp.220–229.

Think.Eat.Save, 2014. *About the campaign*. [Online] available at: <http://www.thinkeatsave.org/index.php/about/about-the-campaign> [Accessed Jun. 2015].

Thyberg, K.L. and Tonjes, D.J., 2015. A management framework for municipal solid waste systems and its application to food waste prevention. *Systems*, 3(3), pp.133–151.

Torrance, G.W., Boyle, M.H. and Horwood, S.P., 1982. Application of multi-attribute utility theory to measure social preferences for health states. *Operations Rresearch*, 30(6), pp.1043–1069.

Turner, D.A., Williams, I.D. and Kemp, S., 2016. Combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making. *Journal of Cleaner Production*, 129, pp.234–248.

UK Green Investment Bank, 2015. *The UK anaerobic digestion market*. [Online] available at: <http://www.greeninvestmentbank.com/media/44758/gib-anaerobic-digestion-report-march-2015-final.pdf> [Accessed May 2015], March.

UNEP, 2011. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication. *Sustainable Development*. ISBN: 978-92-807-3143-9.

UNEP, 2015. *Global Waste Management Outlook*. ISBN: 978-92-807-3479-9.

United Nations, 2014. *Goal 1: Eradicate extreme poverty & hunger*. [Online] available at: <http://www.un.org/millenniumgoals/poverty.shtml> [Accessed Nov. 2014].

United Nations, 2015. *Resolution adopted by the General Assembly on 25 September 2015. Transforming our world: the 2030 Agenda for Sustainable Development*. [Online] available at: <http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E> [Accessed Nov. 2015], October.

United Nations (Department of Economic and Social Affairs), 2013. *World population projected to reach 9.6 billion by 2050*. [Online] available at: <https://www.un.org/en/development/desa/news/population/un-report-world-population-projected-to-reach-9-6-billion-by-2050.html> [Accessed Apr. 2014].

United Nations Statistics Division, 2015. *Central Product Classification*. [Online] available at: <https://unstats.un.org/unsd/cr/registry/cpc-21.asp> [Accessed Jan. 2017].

Vanham, D., Bouraoui, F., Leip, A., Grizzetti, B. and Bidoglio, G., 2015. Lost water and nitrogen resources due to EU consumer food waste. *Environmental Research Letters*, 10(8), p.84008.

Venkat, K., 2011. The Climate Change and Economic Impacts of Food Waste in the United States. *International Journal of Food System Dynamics*, 2(4), pp.431–446.

Ventour, L., 2008. *The food we waste. Food waste report v2.* WRAP, July. ISBN: 1-84405-383-0.

Vögeli, Y., Riu, C., Gallardo, A., Diener, S. and Zurbrügg, C., 2014. *Anaerobic digestion of biowaste in developing countries. Practical information and case studies*. Dübendorf (Switzerland): Swiss Federal Institute of Aquatic Science and Technology (Eawag). ISBN: 978-3-906484-58-7.

Van der Vorst, J.G.A.J., 2000. *Effective Food Supply Chains. Generating, modelling and evaluating supply chain scenarios*. Wageningen University.

Vučijak, B., Kurtagić, S.M. and Silajdžić, I., 2015. Multicriteria decision making in selecting best solid waste management scenario: A municipal case study from Bosnia and Herzegovina. *Journal of Cleaner Production*, 130, pp.166–174.

Wada, K., Takei, N., Sato, T. and Tsuno, H., 2015. Sources of organic matter in first flush runoff from urban roadways. *Water Science and Technology*, 72(7), pp.1234–1242.

Waldron, K., 2007. *Handbook of Waste Management and Co-Product Recovery in Food Processing. Volume 1*. Cambridge (UK): Woodkead Publishing Limited. ISBN-13: 978-1-84569-025-0.

Wang, S., Huang, G.H. and Yang, B.T., 2012. An interval-valued fuzzy-stochastic programming approach and its application to municipal solid waste management. *Environmental Modelling and Software*, 29(1), pp.24–36.

Wang, Y. and Ai, P., 2016. Integrating particle physical geometry into composting degradation kinetics. *Bioresource Technology*, 200, pp.514–520.

Westendorf, M.L., 2000. *Food waste to animal feed*. First edit ed. Ames, Iowa: Iowa State University Press.

Whitehead, P., Parfitt, J., Bojczuk, K. and James, K., 2013. *Estimates of waste in the food and drink supply chain. Final report*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/Estimates%20of%20waste%20in%20the%20food%20and%20drink%20supply%20chain_0.pdf> [Accessed Dec. 2014], WRAP, October.

Whiting, A. and Azapagic, A., 2014. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. *Energy*, 70, pp.181–193.

WHO, FAO, 1995. Codex general standard for contaminants and toxins in food and feed. *Codex Standard 193.*

WHO, FAO, 2016. *Codex Alimentarius General Standard for Food Additives*. [Online] available at: <http://www.fao.org/gsfaonline/foods/index.html?lang=en> [Accessed Jan. 2017].

Wilson, D.C., Rodic, L., Cowing, M.J., Velis, C.A., Whiteman, A.D., Scheinberg, A., Vilches, R., Masterson, D., Stretz, J. and Oelz, B., 2015. 'Wasteaware' benchmark indicators for integrated sustainable waste management in cities. *Waste Management*, 35, pp.329–342.

Wind, Y. and Saaty, T.L., 1980. Marketing Applications of the Analytic Hierarchy Process. *Management Science*, 26(7), pp.641–658.

Winkler, J. and Bilitewski, B., 2007. Comparative evaluation of life cycle assessment models for solid waste management. *Waste Management*, 27(8), pp.1021–1031.

World Commission on Environment and Development, 1987. *Our Common Future*. [Online] available at: <http://www.un-documents.net/ocf-02.htm> [Accessed Jun. 2014], Oxford University Press.

World Resources Institute (WRI), 2013. *Creating a Sustainable Food Future. A menu of solutions to sustainably feed more than 9 billion people by 2050*. ISBN 978-1-56973-817-7.

Worldometers, 2017a. *Current World Population*. [Online] available at: <http://www.worldometers.info/world-population/> [Accessed Jan. 2017].

Worldometers, 2017b. *Water consumed this year (billion of liters)*. [Online] available at: <http://www.worldometers.info/water/> [Accessed Jan. 2017].

WRAP, 2007. *Understanding food waste. Research Summary*. March. ISBN: 1-84405-310-5

WRAP, 2011. *Applying the waste hierarchy: A guide to business*. [Online] available at: <http://www.fccenvironment.co.uk/assets/files/pdf/content/wrap-applying-wastehierarchy.pdf> [Accessed Dec. 2014].

WRAP, 2013. WRAP *Estimates of food and packaging waste in the UK grocery retail and hospitality supply chain*. 21 November.

WRAP, 2014. *Estimates of food and packaging waste in the UK grocery retail and hospitality supply chain*.

WRAP, 2015. *Estimates of food and packaging waste in the UK grocery retail and hospitality supply chain*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/UK%20Estimates%20October%2015%20%28FINAL%29_0.pdf> [Accessed Dec. 2015].

WRAP, 2016. *Digestate and compost use in agriculture. Good practice guidance for agricultural contractors*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/Digestate_and_compost_good_practice_guide_agri-contractors.pdf> [Accessed Apr. 2016], February. Banbury (UK).

WRAP, 2017. *Estimates of Food Surplus and Waste Arisings in the UK*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/Estimates_%20in_the_UK_Jan17.pdf> [Accessed Feb. 2017].

WRAP, 2017. *The Courtauld Commitment 2025*. [Online] available at: <http://www.wrap.org.uk/content/courtauld-commitment-2025> [Accessed Apr. 2017].

WRAP, n.d. *Quality Protocol. Compost. End of waste criteria for the production and use of quality compost from source-segregated biodegradable waste*. [Online] available at: <http://www.qualitycompost.org.uk/upload/cqp_2012.pdf> [Accessed Feb. 2017].

WRAP, n.d. *The Hospitality and Food Service Agreement: Taking action on waste*. [Online] available at: <http://www.wrap.org.uk/sites/files/wrap/Hospitality_and_Food_Service_Agreement_final_report_0.pdf> [Accessed Feb. 2017].

Wu, Y., Wang, C., Liu, X., Ma, H., Wu, J., Zuo, J. and Wang, K., 2016. A new method of two-phase anaerobic digestion for fruit and vegetable waste treatment. *Bioresource Technology*, 211, pp.16–23.

Xu, C., Shi, W., Hong, J., Zhang, F. and Chen, W., 2015. Life cycle assessment of food waste-based biogas generation. *Renewable and Sustainable Energy Reviews*, 49, pp.169–177.

Xu, W., Zhou, C., Cao, A. and Luo, M., 2016. Understanding the mechanism of food waste management by using stakeholder analysis and social network model: An industrial ecology perspective. *Ecological Modelling*, 337, pp.63–72.

Zaman, A.U. and Lehmann, S., 2013. The zero waste index: A performance measurement tool for waste management systems in a 'zero waste city'. *Journal of Cleaner Production*, 50, pp.123–132.

Zhang, C., Su, H., Baeyens, J. and Tan, T., 2014. Reviewing the anaerobic digestion of food waste for biogas production. *Renewable and Sustainable Energy Reviews*, 38, pp.383–392.

Zhang, C., Su, H., Wang, Z., Tan, T. and Qin, P., 2015. Biogas by Semi-Continuous Anaerobic Digestion of Food Waste. *Applied Biochemistry and Biotechnology*, 175(8), pp.3901–3914.

Zhang, R., El-Mashad, H.M., Hartman, K., Wang, F., Liu, G., Choate, C. and Gamble, P., 2007. Characterization of food waste as feedstock for anaerobic digestion. *Bioresource Technology*, 98(4), pp.929–935.

Zhang, Z., O'Hara, I.M., Mundree, S., Gao, B., Ball, A.S., Zhu, N., Bai, Z. and Jin, B., 2016. Biofuels from food processing wastes. *Current Opinion in Biotechnology*, 38, pp.97–105.

Zhao, Y. and Deng, W., 2014. Environmental impacts of different food waste resource technologies and the effects of energy mix. *Resources, Conservation and Recycling*, 92, pp.214–221.

Zheng, W., Phoungthong, K., Lü, F., Shao, L.-M. and He, P.-J., 2013. Evaluation of a classification method for biodegradable solid wastes using anaerobic degradation parameters. *Waste management*, 33(12), pp.2632–40.

APPENDICES

Appendix 1 presents an example of a FW questionnaire used to identify and categorise FW streams in the food companies participating in the case studies (Chapter 10).

Appendices 2-8 present the articles published during the development of the research reported in this thesis:

Appendix 2 Journal paper

A Framework for a More Efficient Approach to Food Waste Management

Appendix 3 Conference paper

A Manufacturing Approach to Reducing Consumer Food Waste

Appendix 4 Conference paper

Manufacturing Resilience via Inventory Management for Domestic Food Waste

Appendix 5 Journal paper

Pickering Particles Prepared from Food Waste

Appendix 6 Journal paper

A Methodology for Sustainable Management of Food Waste

Appendix 7 Journal paper

Optimising Industrial Food Waste Management

Appendix 8 Book chapter

Forging New Frontiers in Sustainable Food Manufacturing

Appendix 1: Food waste questionnaire

Company information	
Name	
Activity	
Location	

Waste number __	
	Example of answers
Type of waste	*Orange skin, meat bones, sandwich in its package…*
Edibility	*Edible / Inedible*
State	*Eatable / Uneatable / Uneatable for humans, eatable for animals*
Origin	*Animal based / Plant based*
Complexity	*Single product / Mixed product*
Animal-product presence	*Meat / Animal product / Animal by-product (categories 1-3) In contact with animal materials / Not in contact with animal materials*
Stage of the supply chain	*Catering waste / Non-catering waste*
Treatment	*Processed / Unprocessed*
Packaging	*Packaged / Unpackaged or separable from packaging*
Packaging biodegradability	*Biodegradable packaging / Non-biodegradable packaging*

Amount of this type of waste	*kg/day, ton/year, l/hour…*
Does this amount of waste change during the year? When and why?	*Yes / No. When yes: food spoils faster during summer, difficulty to forecast demand during holidays causes overproduction and waste, certain foods are only harvested specific times of the year…*
Why is this waste generated?	*Overproduction, inadequate storing practices, wrong processing, unavoidable waste, spilled food, left too long and spoiled, poor communication between departments or other stages of the supply chain…*
Is this waste segregated from other wastes?	*Yes / No*
Current waste management practice	*Landfilling, incineration, landspreading, composting, anaerobic digestion, other industrial uses, animal feed, redistribution…*
Would any investment be required in order to use a better waste management alternative?	*Yes / No*
How much did this ingredient cost?	*£/kg*
What is the economic cost or benefit obtained from the current waste management option?	*Cost / Benefit: £/kg*
How many products does the company produce?	*Number*
In how many products is this ingredient used?	*Number*

Appendix 2: Journal paper

A Framework for a More Efficient Approach to Food Waste Management

This paper has been published in the *International Journal of Food Engineering* and presented by Guillermo Garcia-Garcia at the 1st International Conference on Food and Environmental Sciences on 8-9th February 2015 in Yangon, Myanmar.

This paper cannot be included in this appendix due to copyright reasons. The full text can be found at this link:
http://www.ijfe.org/index.php?m=content&c=index&a=show&catid=114&id=477.

The details of the publication are:
Garcia-Garcia, G., Woolley, E. & Rahimifard, S., 2015. A Framework for a More Efficient Approach to Food Waste Management. *International Journal of Food Engineering*, 1(1), pp.65-72. doi: 10.18178/ijfe.1.1.65-72.

Appendix 3: Conference paper

A Manufacturing Approach to Reducing Consumer Food Waste

This paper has been published in *Advances in Manufacturing Technology XXX* and presented by Miss Aicha Jellil at the 14th International Conference on Manufacturing Research on 6-8th September 2016 in Loughborough, UK.

A Manufacturing Approach to Reducing Consumer Food Waste

Aicha JELLIL[a], Elliot WOOLLEY[a,1], Guillermo GARCIA-GARCIA[a] and Shahin RAHIMIFARD[a]
[a] *Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK.*

Abstract. Globally, one third of food produced is wasted. In the UK, 47% of the food waste is post-consumer revealing a need to encourage more efficient consumption. This research asserts that manufacturers and retailers can play a crucial role in minimising consumer food waste (CFW) through consumer engagement and provision of smart solutions that ensure more efficient use of food products. Supporting manufacturers and retailers to minimise CFW can be achieved via two stages: a) understanding and evaluating CFW, and b) identifying improvements to manufacturing and retail activities that would reduce CFW. On-site waste audits have identified that the percentage of edible CFW from domestic environments (77%) is greater than that disposed of in public areas (14%) supporting the hypothesis that improving the full food provisioning process (e.g. packaging, storage, guidance) would be beneficial. This paper proposes a number of mechanisms to support manufacturing and retail in reducing CFW.

Keywords. Consumer food waste, food manufacturers, retailers.

1. Introduction

It is estimated that in developing countries about 40% of food waste is generated at post-harvest and processing stages, whereas 40% of food waste in the developed countries is created at the retail and consumer stages [1]. This research focuses on consumer food waste (CFW) generated in the UK, as a representative of developed countries, which is estimated to amount to 7 MT p.a. out of a total of 15 MT p.a. of food wasted in the UK [2]. This makes UK consumers the largest single contributor towards food waste (Figure 1). Moreover, 60% of CFW in the UK is estimated to be avoidable [3]. CFW has the highest level of environmental and economic impacts compared to waste generated at other stages of the supply chain and this is due to the significant amount of resources (water, labour, etc.) used to produce the final products.

Several factors contribute to CFW generation including consumer behaviour, retail environment (e.g. promotions, packaging) and other external factors (e.g. economic, governmental) [2]. These three main factors highly influence how consumers purchase, store, prepare and consume food which in turn influence consumer generation of waste. Therefore, CFW is not just an issue of individual behaviours [4] and manufacturing and retail have the power to influence the consumer choices and improve their business activities in order to reduce domestic food waste. This paper presents an overview of

[1] Corresponding Author. E.B.Woolley@lboro.ac.uk

the approaches suggested for businesses to minimise CFW, proposes a new approach for manufacturers and retailers to support efficient consumption and discusses findings from on-site food waste audits conducted at domestic properties as well as public areas.

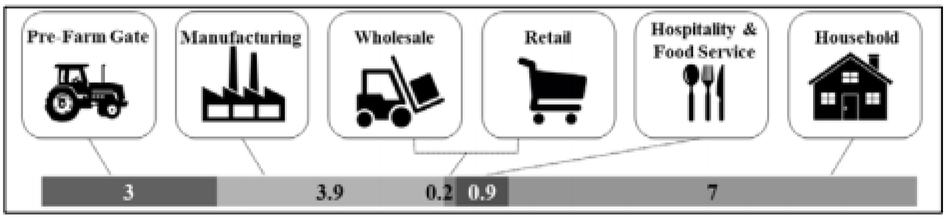


Figure 1. Food waste in the UK by stage (in million tonnes). Data from [5].

2. Consumer Food Waste Reduction

A review of the literature has identified several proposed (or implemented) solutions for manufacturers and retailers to support the reduction of CFW. These solutions can be categorised into strategic or functional. It was observed that only a minority of these solutions focuses on reducing CFW in terms of environmental impact. This deserves more attention as reducing the waste of a certain food product by a small quantity (e.g. beef) can have better environmental benefits than reducing a greater amount of waste generated from another product (e.g. potato).

For the solutions that can be implemented at a strategic level, several frameworks have been identified; some of these are detailed in Table 1. All of these frameworks stress the importance of deploying communication, technology and policy making in supporting consumers to minimise their food waste.

At a more functional level, some actions were taken to reduce CFW by extending food shelf-life, offering more variety for food portion size, providing storage guidance and clarifying food date labels. These actions are important since 80% of avoidable CFW is due to factors such as: *"Cooked, prepared or served too much"* (48%) and *"Not used in time"* (31%) [3]. Most of the offered solutions rely on improving food packaging as it constitutes a medium to communicate with consumers.

Resealable packaging and packaging that reduces cross-contamination (e.g. pre-cut packaged ingredients) are examples of solutions that extend food shelf life at home and provide more flexibility for portioning [6].To keep food fresh for longer and to utilise it efficiently, packaging has been used to provide clear guidance on how to store food [2] and phone apps have been proposed to help consumers manage their food inventory [7]. Regarding date labelling, some actors called for the "abolishment of best-before labels for long-lasting products" [8] since some consumers use "this label as a 'use by' date, rather than a quality guideline" [9]. To overcome the confusion over food date labels, temperature sensitive colour changing smart labels, made of gold nanorods, have been suggested to enable a more precise indication of whether the food is spoilt or not [10].

The proposed solutions are effective ways for manufacturers and retailers to help solve issues stated as direct causes for food waste (e.g. products perishability); however, the majority of these approaches focus on short-term interactions with consumers. They regard provision of food as simple transactions instead of a medium to build stronger relationships between businesses and consumers. For instance, provision of guidance on how to use a product does not take into consideration the environment in which that product will be prepared and used as well as its interaction with other food products.

Table 1. Frameworks for reducing consumer food waste.

Innovate, Influence Edit Framework [11]	4 E's Framework [12]	UNEP Guidance [13]	Working on Waste Framework [14]
Innovate: integrate sustainability into product design innovation	**Exemplify**: lead by example; achieve consistency in policies	**Plan**: a strategy to engage consumers	**Use technology**: to facilitate reduction of food waste
Influence: use communication to enable consumers to choose products more sustainably	**Enable**: remove barriers; provide facilities, alternatives; train; educate	**Set targets**: establish a baseline	**Tailor messages**: to the occasion, keep it simple in store
Edit: remove unsustainable products, product components and services from marketplace	**Encourage**: tax system; reward schemes; penalties	**Develop**: evidence-based guidance	**Create value**: by being specific with technical solutions and communication
	Engage: communication; media campaigns	**Act**: to prevent food waste	
		Evaluate: measure, monitor and report progress	

3. A Manufacturing Approach for Addressing Consumer Food Waste

As discussed in the previous section, the majority of the solutions proposed to minimise CFW regard manufacturers/retailers–consumers relationship as transactional. Transactional exchanges (Figure 2) refer to those "anonymous transactions" where both the buyer and supplier seek to "win at the other's expense" [15]. The idea is for manufacturers and retailers to move towards the right of the relationship spectrum (Figure 2) by adopting value-added exchanges where they should improve their understanding of consumer behaviour (needs, attitudes, habits, etc.) leading to the generation of food waste and then formulate adequate and targeted solutions that would remove the barriers to a more environmentally sustainable consumption.

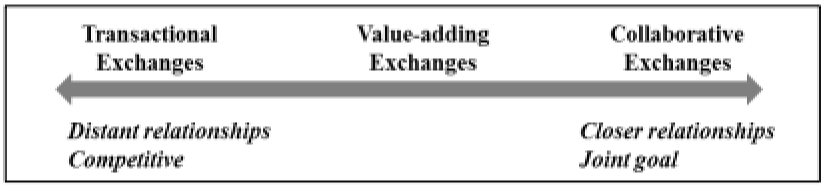


Figure 2. Buyer seller relationship spectrum. Adapted from [15].

In order for manufacturers and retailers to build strong relationships with their customers, they need to acquire three main capabilities: a) the mind-set of the organisation should be relationship-oriented so that its culture is focused on interacting with consumers before, during and after purchase; b) the organisation needs to continually deepen its knowledge of its customers; c) and the organisation process needs to be integrated and aligned with the customer's process [15].

A possible approach to integrate manufacturers and consumers processes would be the servitization of food manufacturing. Servitization is "[when] the manufacturer [act] as a service provider that sets out to improve the process of their customers through a business model rather than product-based innovation" [16]. It leads to the offering of a combination of goods and services, support, knowledge and/or self-service [17]. This concept has been mainly applied to products that do not cease to exist once they are used (e.g. washing machines); however, it can also be applied to consumable products [18] and therefore to the food sector. Thus, food manufacturing servitization would enable manufacturers and retailers to support consumers during the whole food provisioning process and in managing their domestic food related operations efficiently.

This research asserts that for manufacturers and retailers to support consumers in minimising CFW, they should first acquire a strong understanding of their customers and then change their internal activities to align them with the consumption process (demonstrated in Figure 3). This should enable the manufacturers and retailers to supply the right offering to the right consumer, resulting in a reduction of CFW.

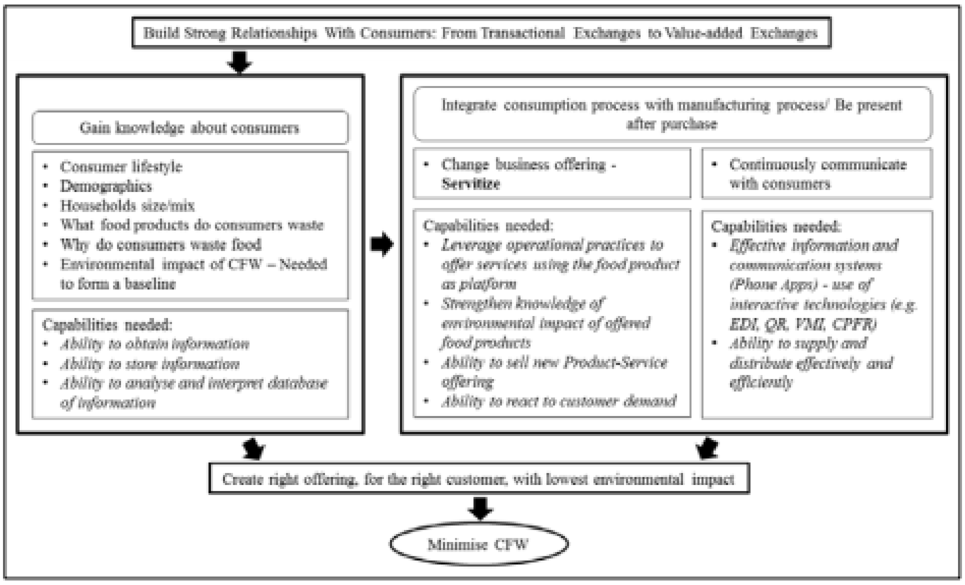


Figure 3. Proposed approach to minimise CFW in this work.

Servitization is advantageous to manufacturers as it enables them to gain a competitive edge by 'locking in' customers, setting up barriers to competitors and differentiating the market offer [17]; however, there exists some risk associated with implementing it. First, the early transition to servitization could be challenging depending on the market offering: manufacturers need to ensure that they have the capability to sell their product-service offering. The second risk concerns in the investment cost needed to make this strategic transition which includes: the initial capital needed to change the technical and organisational structure, and the additional transitional cost arising from producing the new offering such as costs of building new customer relationships [19]. The third risk is associated with the cost of production [19] as the manufacturing operations would be affected by the interaction with customers which would create uncertainties and increased variations.

4. Case Study

In order to better understand CFW and support the assertion that manufacturers and retailers play a crucial role in minimising CFW by collaborating with consumers, several food waste audits were conducted in public areas as well as domestic halls at Loughborough University. The university was chosen as it constitutes a good representation of an urban area. The investigations took place in three different living halls, the library and one of the university's major schools. A total of 74.35 kg of general waste was audited where six general waste bags were collected from each facility and food waste was categorised into edible/inedible, animal/plant based and packaged/unpackaged. These three food waste categories were selected from a nine-stage classification proposed by Garcia *et al.* [20]; the remaining six categories in the aforementioned classification were not considered relevant in this investigation.

The analysis of the data obtained from the audits revealed that the proportion of edible food waste is significantly greater in the living halls compared to the public areas as shown in Figure 4. This observed difference can be explained by suggesting that consumers generate more edible food waste in domestic environments (kitchens) where food preparation, food inventory management as well as food consumption occurs; conversely, in public areas, it is expected that edible food waste is mainly a result of consumption in the absence of preparation or stock management.

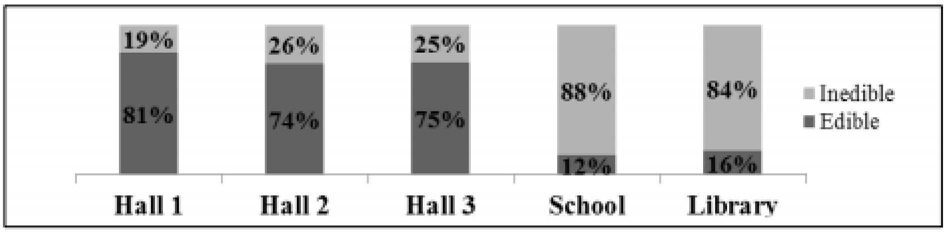


Figure 4. Food waste audits results for the edible/inedible category.

The investigation's result justifies the need for manufacturers and retailers to support consumers through their full food provisioning process in order to minimise CFW and this by adopting the aforementioned proposed approach (Figure 3) to: create innovative business offering which uses the product as a platform to provide services, knowledge and support that would enable consumers to be efficient in managing their food related operations; tailor their solutions so that products be customised depending on consumers' needs; and engage the consumers through continuous communication supported by effective information systems.

5. Concluding Discussion

This work has highlighted the importance of manufacturers and retailers to foster more efficient and responsible food consumption and presented an overview of the efforts that have been made to support businesses in reducing CFW. The review has identified that the majority of the existing solutions regard manufacturers/retailers–consumers relationships as transactional and thus fail to consider the highly complex domestic environment where food related operations take place.

A proposed solution to solve this complex issue is to strengthen manufacturing and consumption relationship and this by: a) acquiring a deep knowledge of consumers, b) changing business offering through the servitization of food manufacturing and c) effectively communicating with consumers to adapt to their needs by using strong information systems and technologies.

This approach is a result of preliminary findings from an ongoing research project and does not cover elements necessary to change the mind-set of the organisation from offering products to offering products and services. Changing the organisation mind-set is regarded to be an important component to create more collaborative manufacturers/retailers-customers relationships.

Acknowledgements

This research is funded by the Engineering and Physical Sciences Research Council (EPSRC) UK through the grant EP/K030957/1.

References

[1] FAO, Save Food: Global Initiative on Food Loss and Waste Reduction, (2016), [online] Available at: http://www.fao.org/save-food/resources/keyfindings/en/, [Accessed 11/04/2016].
[2] WRAP, From Concept to Consumer Preventing Food Waste in the Home – How can you and your business make an impact?, (2014).
[3] WRAP, Household Food and Drink Waste in the United Kingdom 2012, (2013).
[4] D. Evans, Blaming the consumer – once again: the social and material contexts of everyday food waste practices in some English households, *Critical Public Health*, **21** (2011), 429-440.
[5] WRAP, Estimates of Food and Packaging Waste in the UK Grocery Retail and Hospitality Supply Chains, (2015).
[6] C. K. Sand, Decreasing Consumer- Derived Food Waste. *Food Technology Magazine*, (2015).
[7] E. Woolley, G. Garcia-Garcia, R. Tseng, S. Rahimifard, Manufacturing resilience via inventory management for domestic food waste, *CIRP*, **40** (2016), 372-377.
[8] A. Adam, Drivers of Food Waste and Policy Responses to the Issue: The Role of Retailers in Food Supply Chains, (2015).
[9] WRAP, Consumer Insight: Data Labels and Storage Guidance, (2011).
[10] C. Zhang, A. Yin, R. Jiang, J. Rong, L. Dong, T. Zhao, L. Sun, J. Wang, X. Chen, C. Yan, Time–Temperature Indicator for Perishable Products Based on Kinetically Programmable Ag Overgrowth on Au Nanorods, *ACS Nano*, **7** (2013), 4561–4568.
[11] WBCSD, Sustainable Consumption Facts and Trends from a Business Perspective, (2008).
[12] DEFRA, Securing the Future – Delivering UK Sustainable Development Strategy, (2005).
[13] UNEP, Prevention and Reduction of Food and Drink Waste in Businesses and Households - Guidance for governments, local authorities, businesses and other organisations, (2014).
[14] IGD, Celebrating Food: The Opportunities Surrounding Household Food Waste, (2015).
[15] G., Day, Managing Market Relationships, *JAMS*, **28** (2000), 24-30.
[16] T. Baines, H. Lightfoot, *Made to serve: how manufacturers can compete through servitization and product-service systems*, Wiley, Chichester, 2013.
[17] S. Vandermerwe, J. Rada, Servitization of Business: Adding Value by Adding Services, *European Management Journal* **6** (1988), 314-324.
[18] A. Neely, Is *Servitization for You?*, (2012), [online] Available at: http://andyneely.blogspot.com/2012/02/is-servitization-for-you.html, [Accessed 25.04.2016].
[19] A. Tukker, Eight types of product-service system: eight ways to sustainability? Experiences from SusProNet, *Business Strategy and the Environment*, **13** (2004), 246-260.
[20] G. Garcia-Garcia, E. Woolley, S. Rahimifard, A framework for a more efficient approach to food waste management, *International Journal of Food Engineering*, **1** (2015), 65–72.

Appendix 4: Conference paper

Manufacturing Resilience via Inventory Management for Domestic Food Waste

This paper has been published in *Procedia CIRP* and presented by Dr Elliot Woolley at the 13th Global Conference on Sustainable Manufacturing on 16-18th September 2015 in Ho Chi Minh City / Binh Duong, Vietnam.

Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 40 (2016) 372 – 377
www.elsevier.com/locate/procedia
13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use

Manufacturing resilience via inventory management for domestic food waste

E. Woolley[a]*, G. Garcia-Garcia[a], R. Tseng[ab], S. Rahimifard[a]

[a]*Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University, LE11 3TU, UK*
[b]*Hyflux Ltd, 80 Bendemeer Road, 339949, Singapore*

* Corresponding author. Tel.: +44 (0)1509 225410; *E-mail address:e.b.woolley@lboro.ac.uk*

Abstract

The ability to feed 9 billion people by 2050 will rely on processed foods being delivered through complex and dispersed international supply chains. Currently as much as a third of all food grown is lost as waste at various points along existing supply chains, with roughly half of food waste in the developed world occurring after purchase by the end consumer. For the long-term resilience of the food industry, and as holders of critical information, manufacturers need to play a part in reducing this waste. Using a novel method of food waste categorization, this research describes how the prevention of food waste for certain categories can be facilitated using a Smart Phone App that enables industrial inventory management for the domestic environment, providing the consumer with supporting information about food condition and appropriate preparation processes. Data availability issues and the benefits in terms of resource efficiency and consumer loyalty are discussed.

Peer-review under responsibility of the International Scientific Committee of the 13th Global Conference on Sustainable Manufacturing

Keywords: Food Waste; Environment; Inventory; Consumer Behaviour.

1. Introduction

It has been estimated that as much as 50% of all food that is produced never actually enters a human mouth [1]. This amounts to a potential two billion tonnes of food waste per year, revealing a significant waste of farmland, time, energy, water and money. As the global population moves toward 9 billion people by 2050 the pressure on agriculture and the manufacturing industry to provide sufficient food for the global population will continue to increase [2]. One way of reducing this pressure is to improve the efficiency of the entire food supply chain to reduce inefficiencies in terms of food waste.

Clearly depending upon the region of the world, food waste occurs for a wide range of reasons. The IMechE categorized different reasons in their 2013 report [1] which defined three distinct types of country: Fully developed, late-stage and newly developing countries. The focus of this research is on the waste generated in the UK (as an example of a fully developed country) which has been shown to be split across the supply chain (see figure 1) with 3 million tonnes from farms, 3.9 million tonnes from manufacturing and almost half of all food waste (7 million tonnes) occurring after food products have been purchased by the consumer [3 - 7].

The need for the reduction of food waste throughout the manufacturing supply chain is now well recognized [8] but there has been little incentive to reduce the waste generated by consumers. Industry and retailers are not incentivized as the purchase of more products equates to larger profits. However this business arrangement (overproduce, purchase and discard) not only carries significant environmental impact, but also reduces the ability of established supply chains to meet the growing global demand for food [9]. Therefore a focus on reducing consumer food waste is required in order to reduce this environmental impact and increase the long term resilience of existing supply chains.

Peer-review under responsibility of the International Scientific Committee of the 13th Global Conference on Sustainable Manufacturing
doi:10.1016/j.procir.2016.01.070

Fig. 1. The breakdown of UK food waste. Data from [3 - 7].

Manufactures have a range of tools and techniques to help reduce the production of waste and these can be replicated across different industries. Unfortunately consumers do not act as organizations and both crowd and individual behavior patterns are difficult to predict [10]. As an additional complication, food manufacturing has many differences to other sectors including short product shelf lives and perceived low value. A key challenge therefore is to enable consumers to have similar waste prevention and management techniques to industry, thus facilitating a reduction in food waste generation. To put this into perspective, it is possible, in simple terms, to envisage a consumer as a micro manufacturer (figure 2): they buy raw materials (ingredients), which they store (in cupboards, refrigerators, freezers) and then use a wide range of range of processes (such as mixing, cooking) to produce a final product (meals) to meet a demand (themselves, family, etc.). However, they do not have access to the powerful tools that industry has such as inventory management or materials requirement planning (amongst many others).

In this research it is proposed that access to inventory planning type tools would improve the ability of the consumer to better manage their ingredients and stock and therefore reduce overall food wastage. On the assumption that all food prevented from waste is not additional consumption, this result would alleviate strain on, and therefore increase resilience of, the food manufacturing industry.

In this context, this paper reviews existing domestic food waste and seeks to understand which food types are most problematic, presents a novel food waste categorization process, and describes the development of, and roles of supply chain partners in supporting, a mobile application (App) that facilitates consumer inventory management. This solution is evaluated and a continuation of the work is discussed with respect to implementation.

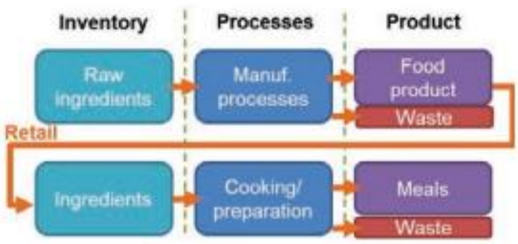


Fig. 2. Consumers as micro manufacturers

2. Current activities for food waste minimization

There are a number of ways to quantify food waste (e.g. by weight, cost, calorie content, environmental impact) but the majority of published literature refers to weight. This might be misleading because some food types are comprised largely of water and have little environmental impact (such as home-grown apples) or are expensive but have low calorie content (e.g. saffron). In this respect it is important to select appropriate metrics for evaluation to avoid unintended outcomes.

Ideally the current research would cover all developed countries but reliable data on domestic food waste could not be obtained. The focus therefore remains on the UK issue, for which a number of reports exist, but which is deemed to be largely representative of other fully-developed countries.

The UK generates about 15 million tonnes of food waste per year [4] with almost half of this attributable to the consumption stage of its life cycle. From UK households, the amount of food waste has decreased from 8.3 to 7.0 million tonnes between 2007 and 2012 [3, 7]. It is important however to understand that not all food waste is avoidable since various components are not edible (e.g. egg shells, meat bones). Various definitions of food waste exist and have been discussed [11] but for domestic waste in this research it is possible to have two main categories, unavoidable and avoidable (this latter category includes food waste which some people eat but others do not such a bread crusts and potato skins). It is estimated that 4.2 million tonnes UK domestic food waste is avoidable [12] with the cost of avoidable food waste for a family of four estimated at £720 (US$1,100) per year.

Food waste can be further divided into types of food such as fresh fruit, ready meals and meat products (see figure 3). The aforementioned difference between weight and cost of food waste is evident, but of interest in this research is the environmental impact. Animal products typically have higher environmental footprints due to the resources required to grow their food, land and water requirements, and greenhouse gas emissions associated with livestock. Similarly, highly processed foods may require a large number of processes, have long supply chains and may have travelled thousands of miles.

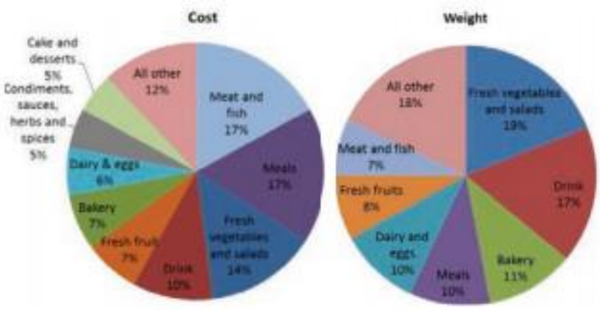


Fig. 3. Comparing UK domestic food waste in terms of cost and weight. Adapted from [13].

Key to providing a solution is to understand why various types of food waste are generated by consumers. Little work appears to have been published on this topic but it has been reported that there is some confusion by consumers over 'Use By' and 'Best Before' dates provided on products [14]. Some analysis has been provided Boyer [15] as to the recommended length of days that fruit and vegetables remain edible, but this clearly also depends on the period of time before purchase, their storage conditions and initial ripeness.

In order to influence the design of a solution for better food waste management, it is therefore necessary to better understand why certain food types (high weight, cost, environmental impact) are wasted by consumers. The remaining sections of this paper are concerned with this objective.

3. Research methodology

It is understood that consumers are 'responsible' for a considerable amount of food waste and therefore the supply chain would be happy to attribute the environmental impact of this waste to consumers rather than shoulder the impact themselves. However, it is not clear from the literature reviewed precisely why food waste is created by the consumer. In order to better understand this, a micro-survey was undertaken to establish the amount of waste discarded and the reasons for this.

Over the period of seven days, ten volunteers recorded a description of the food waste, its weight and the reason for discarding within their homes (figure 4). The volunteers were from a range of ages, gender, occupations and inhabited different types of residential housing. In an ideal situation, the subjects would not know that they were being studied as this might lead to an adaptation of behavior and lead to artificially enhanced levels of food waste prevention. Such a study would also contravene research ethics and so in this work, volunteers were informed of the intention of the study.

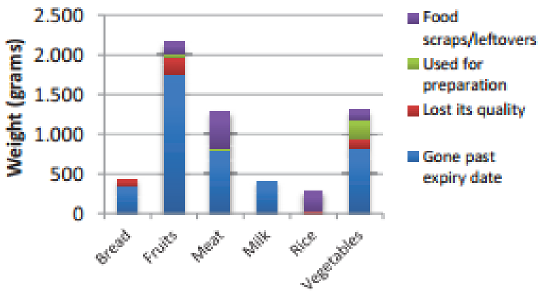


Fig. 4. The most commonly reported food wastes and reasons for their disposal.

From the survey conducted, 60% of food waste was generated due to items having gone past their expiry date, indicating that the management of food inventory is difficult in domestic environments. From figure 3 it is possible to identify that for their weight, the cost of meat and fish is relatively high, as is the environmental impact of these types of food [16]. In addition, such food types are known to carry higher risk of food poisoning and so are unlikely to be consumed after the Use By Date, unlike other food types (e.g. fresh produce, bakery items) which are more likely to be consumed after the Use By Date.

In this respect, the case for inventory management of food products within a domestic environment is made, with an emphasis on the provision of the 'Use By Date' for quickly perishable foods. Other methods of reducing food waste might include extension of shelf life through improved processing, better packaging solutions or faster supply chains, however these improvements are outside of the scope of the current work. In order to harness the power of inventory management within the domestic environment, there needs to be a transfer of data regarding items purchased and associated Use By Dates. Such dates are available to the manufacturer (they define and print them) and are used by the retailer (e.g. for stock rotation). The consumer does not take ownership of the data regarding their purchases except on their till receipt, or increasingly, electronically from on-line shopping. However the list of items purchased does not contain information pertaining to Use By Date of products, and this is critical for the management of inventory.

In addition to the flow of information, there is a need for an inventory management tool that can be used by the consumer to audit, review and plan the use of food products, similar to the way that Enterprise Resource Planning (ERP) systems support businesses. In order for prioritization of consumption of foods (which may be approaching their Use By Date) there is a need to analyze the type of food in question. Without holding or calculating data for every food type, a more simple way of analyzing the cost, environmental impact, etc., of food is by categorization. A nine stage classification process has been developed for industrial waste management [11] of which four stages are applicable here enabling an indication of the above criteria pertaining to a potential waste. The abridged categorization process addresses four criteria; origin, complexity, animal product presence and treatment as described below.

1. Origin: Animal based or plant based – implications of environmental impact and ramifications for waste handling
2. Complexity: Single or mixed ingredient –
3. Animal product presence: Animal product, by product from animal bodies, contact with animal-based products
4. Treatment: processed or unprocessed - implications of environmental impact and ramifications for waste handling

Such categorization is useful for limiting the overall environmental impact from waste which is 'inevitably' generated and also has the potential to assist consumers with improvement of waste handling.

4. Inventory management for domestic consumers

The intention of this work is to provide a food inventory management system for the domestic user. The data requirement is for the user to have clear visibility of the use-by dates for key food products and thus be able to minimize wastage of these product categories. Information therefore needs to be passed from the food manufacturer, through the retailer and to the customer in a form that is easily accessible. For the purpose of this problem, any logistics activities play a passive role, since they are not concerned with individual products but only batches of product, which have different information requirements.

In this respect, there are three main actors, defining three stages, that are of concern in any solution that could provide the required inventory management: stage 1: the manufacturer, stage 2: the retailer and stage 3: the consumer.

Stage 1: The Manufacturer. The primary information requirement is the Use By Date which needs to pass from the manufacturer to the product to the consumer. This is currently achieved by a lawfully printed date on each product. However the format and location (front, top, bottom, side of product) of this printed date varies hugely and so it is unlikely that an image capture system would be successful in reading this date and the point of sale (POS). Therefore a number of different options were considered as tabulated below.

Table 1. Options explored for recording Use By Date at POS.

Information system	Required reader
Standardization of expiry date stamp (e.g. next to barcode)	Optical character recognition adjacent to barcode reader
Magnetic ink	Magnetic ink character recognition adjacent to barcode scanner
Radiofrequency identification embedded into packaging	RFID reader at POS
Multi-field barcode (e.g. GS1 DataBar)	Standard barcode reader

Of the above solutions, the multi-field barcode offers the easiest solution since no additional hardware is required at POS and only minor modifications would need to be made to the product packaging. The major change would be that the barcode for the product could only be printed during the final stages of manufacture or after the product has been packaged as this barcode would contain the Use By Date data of the product (which changes daily).

Stage 2: The Retailer. The data that is ultimately required by the consumer is the item name, expiry date, date of purchase, origin, complexity, animal product presences and treatment. Apart from expiry date and date of purchase, all fields will remain unchanged and can therefore be referenced from a database. At the POS, it is therefore only the expiry date, date of purchase that need to be generated, which are possible following the recommendations in Stage 1.

These fields of information need to be made available to the consumer inventory management tool for which there are two options: Near field communication (NFC) onto a smart phone, or storage on a 'loyalty card' system and accessible via the internet. NFC uses radio communication (13.56 MHz) by proximity (~100mm) to transfer data to a compatible device at baud rates of 100's kbit/s. Although a suitable solution, such a technology would need to be installed at every POS, would only be suitable for consumers with particular types of smart phones and requires an additional procedure at checkout.

In contrast, a loyalty card system approach would utilize existing data infrastructure within retailers to record the purchases made by a consumer with the associated fields including expiry date. This register of information could then me made available to the consumer via secure internet link, providing the opportunity for the consumer to manage inventory via mobile or static internet device.

Stage 3: Consumer. Once the consumer has access to the required fields, there is a need for an inventory management programme and interface. In this work an app has been developed for use on a smart phone, but the programme is equally applicable for use on tablets or PCs. Three main functions were considered and developed:

- **Stock List** - allows users to keep inventory of their food items already purchased, including expiry dates. Modifiable to remove items already consumed, partly consumed or disposed of.
- **Expiry Tracker** - notifies the user when items are about to exceed Use By Date. Dependent on settings, alarm activates *n* days before expiry date. Once alarm triggers, four options are provided consumed, partly consumed, not consumed, wasted. Alarm can be 'snoozed' for *m* hours before reminder sent.
- **Recipe Recommendation** - depending upon the items highlighted by the Expiry Tracker function, a number of recipes using these ingredients and others within the Stock List can be identified via the internet and suggested to the user.

The pathway for the introduction of an inventory management tool for consumers therefore comprises of the three solutions as shown in figure 5. The development of the App is further described in section 5.

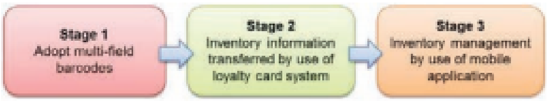


Fig. 5. Three stages of information flow for domestic inventory management of food.

5. App Development

A mobile application, entitled *Pantry*, was programmed using graphical interfaced, cloud-based, MIT App Inventor 2. This programme was used to create the front-end application described in this section, but also required the use of a Backend as a Service (BaaS), in this case Parse. BaaS is a model for providing mobile apps with a way to link to backend cloud storage, which for this application would be the information recorded by the retailer regarding a customer's purchases. An application programming interface (API) between the front end and backend service allows the provision of features such as user management, push notifications, and integration with social networking thus opening up opportunities for retailer marketing and reward schemes.

In order to receive data regarding items which need to be kept in Pantry's inventory, the requests are required to be in JavaScript Object Notation (JSON). Table 2 describes the fields required by Pantry in order to populate the Stock List. Request for updates can be done manually by the user, or automatically at user defined intervals or from preset triggers (e.g. push request from store). Since not all food items may be bought from a store with a loyalty card system that can be accessed by an App, it is also possible manually input products into the Stock List of Pantry.

Table 2. Fields required by Pantry for Stock List.

Name	Type	Description
userId	String	userId is a string unique to the class User that identifies this object.
productId	String	An identification to the product which can be used to access additional data from the web.
productStatus	Integer	0 for inactive entries, 1 for active entries
productPrice	Decimal	The product price, without currency sign, or thousand separators.
productName	String	Product name
expiryDate	String/ date	Expiry date UTC timestamps stored in ISO 8601 format.
imgSrc	String	A string containing the image source.
productUnit	String	A string that identifies the product unit, which must exist as an object in class *Unit*.

The Stock List is then kept locally on the device with a graphical user interface that is intuitive for consumers (figure 6). At the top-level, the data shown from the database, provides an item description, categorization as defined in section 4, days left (before expiry) and a Boolean indicator for eaten/not eaten.

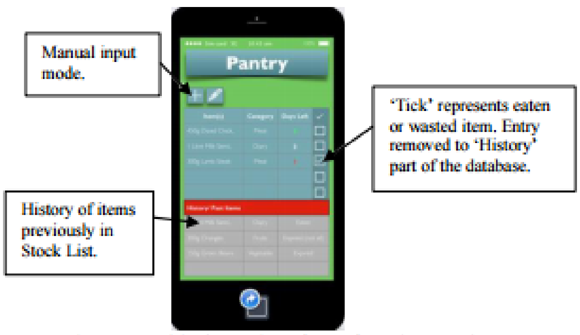


Fig. 6. Graphical user interface of Expiry Tracker.

The Expiry Tracker operates in parallel with the stock list and refers to user defined preferences to trigger alarm notifications. The user has the option of selecting eaten, partly eaten, not eaten and wasted for items reported by the Expiry Tracker as well is inputting new expiry dates (e.g. for opened or cooked meat). Once an item has been eaten or has expired, it is moved into the recent history part of the database, where it is stored and displayed for a user defined period of time.

In the current study, the Recipes Recommendation function was not incorporated into the app as no existing suitable recipe database could be found. The query information requires access to the items remaining in the Stock List, with preference given to the items with the shortest remaining life and of key categorizations (e.g. high environmental impact). Other items that exist in the stock list are used to identify a number of suitable recipes for the user. Advanced versions of the Recipe Recommendation function could link to retailer internet shopping sites for easy purchase of additional items and even be linked to a meal planner.

6. System testing

A number of barriers relating to data availability and limitations of the programming software used prevented extensive testing of Pantry. However, dry-process testing was carried out on a small scale to demonstrate the functionality of Pantry. This section describes the limitations and testing of the developed inventory management tool.

In terms of the Stock List, currently there is no commercial system in place that enables customer of food retailers to have access to Use By or Best Before Dates of foods purchased. In addition to this, large UK superstore websites will not currently accept requests via java script and any information held about products purchased (e.g. via on-line shopping) cannot be obtained by the current version of the app. These limitations mean that product information and expiry dates must be entered manually into Pantry for system testing.

From the perspective of the Expiry Tracker, apps created using MIT App Inventor 2 cannot run in the background as services, and this imposed a critical limit to the functionality of the current version of the app. A warning that food is about to expire could only be triggered if the user actually has the application open, which is not convenient for the majority of users. In response, bespoke alarms were set for individual food items which sounded three days before the expiry date, and repeated every 24 hours.

System testing was carried out by a small number of consumers over a week-long period, and was concerned with five types of food: meat, fruits, vegetables, milk and bakery items. Items bought and expiry dates were manually recorded and alarms set for three days prior to the expiry date. Although suggestive of reductions in food waste, results were not conclusive and would need to incorporate a comparison with a control group of consumers or significantly larger sample of participants. Despite this, for the five types of food studied over the testing period, a reduction of 34% of food discarded was recorded. Scaled-up for all food types in the UK, this would equate to savings of circa 1.5 million tonnes of food waste per annum. As stated, it is not possible to determine how much of this reduction was due to the use of the Pantry system for domestic inventory planning, and how much could be attributed to the heightened awareness of expiry dates from dedication to using the system. Perhaps it does not matter since the end result is beneficial, but the real benefit would be in sustained reductions in food waste, and for this it is suggested that an easy-to-use inventory management system (such as the Pantry app) would be better able to deliver this.

7. Conclusions

From the literature reviewed in the early sections of this paper it is clear that a large percentage of food waste in the developed world is generated after final purchase by the consumer. It seems misdirected therefore, that the majority of efforts to reduce food waste by industry focus on reducing internal waste production and not along the remainder of the supply chain. In this respect, this work has highlighted the opportunity for the manufacturing industry to assist consumers in reducing the amount of food they waste by developing tools prevalent in industry for the domestic environment. In this context this work has demonstrated the importance of short shelf life food types such as meat and dairy which carry larger economic value and environmental impacts.

A proposed solution is an inventory management tool suitable for consumers, to manage ingredients bought from retailers. Such a tool, which has roots in material requirements planning, can be supported by recording and transferring data regarding product Use By Dates to consumers, for which a number of mechanisms are discussed. A mobile application-based approach is described involving the key capabilities of Stock List and Expiry Tracker to enable consumers to better monitor the food items they have within their domestic environment and to consume these before the expiry date is met.

The app, which was developed in MIT App Inventor 2, is described in detail and preliminary system testing is undertaken. The implementation and benefits of the app are discussed with early results showing a reduction of 34% food waste across key food types. However collaboration with a large grocery retailer, incorporating advances in expiry date communication and testing over long periods with a greater number of participants is required for conclusive results to be drawn.

The solution of domestic inventory management proposed in this work is just one of many potential methods that the manufacturing industry can assist domestic consumers in reducing food waste.

References

[1] IMechE, 2013. *Global Food Waste Not, Want Not*, Institute of Mechanical Engineers, London.
[2] Charles, H., Godfray, J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., & Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People, *Science*, **327**, 812-818.
[3] Waste and Resources Action Plan (WRAP), 2013. *Estimates of Waste in the food and drink supply chain.*
[4] Waste and Resources Action Plan (WRAP), 2014. *Estimates of food and packaging waste in the UK grocery retail and hospitality supply chain.*
[5] Department for Environment, Food and Rural Affairs (DEFRA), 2012. *Food Statistic Pocket Book.*
[6] Waste and Resources Action Plan (WRAP), 2010. *Waste arisings in the supply chain of food and fring to households in the UK.*
[7] Waste and Resources Action Plan (WRAP), 2011. *New estimates for household food and drink waste in the UK.*
[8] Kummua, K., de Moelb, H., Porkkaa, M., Siebertd, S., Varisa, O., Wardb, J., 2012. Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use, *Science of the Total Environment*, **438**, 477-489.
[9] Gunders, D., 2012. *Wasted: How America Is Losing Up to 40 Percent of Its Food from Farm to Fork to Landfill*, Natural Resources Defense Council, USA.
[10] Whan Park, C., Iyer E.S., Smith, D.C., 1989. The Effects of Situational Factors on In-Store Grocery Shopping Behavior: The Role of Store Environment and Time Available for Shopping, *Journal of Consumer Research*, **15**, 422-433.
[11] Garcia-Garcia, G., Woolley, E., Rahimifard, S., 2015. A framework for a more efficient approach to food waste management, *International Journal of Food Engineering*, **1**, (1), 65-72.
[12] Quested, T., Ingle, R. & Parry, A., 2013. *Household Food and Drink Waste in the United Kingdom 2012*, WRAP.
[13] Waste and Resources Action Plan (WRAP), 2013. *Overview of waste in the UK hospitality and food sector.*
[14] Waste and Resources Action Plan (WRAP), 2011. *Guidance on the application of date labels to food.*
[15] Boyer, R., 2009. *Food Stoarge Guidelines for Consumers.* Virginia Cooperative Extension.
[16] Berners-Lee, M. 2010. *How Bad Are Bananas?* Profile Books, London.

Appendix 5: Journal paper

Pickering Particles Prepared from Food Waste

This paper has been published in the special issue Pickering Emulsion and Derived Materials in the journal *Materials*.

materials MDPI

Article

Pickering Particles Prepared from Food Waste

Joanne Gould [1,*], Guillermo Garcia-Garcia [2] and Bettina Wolf [1]

[1] Division of Food Sciences, School of Biosciences, The University of Nottingham, Sutton Bonington Campus, Loughborough LE12 5RD, UK; bettina.wolf@nottingham.ac.uk

[2] Centre for SMART, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK; G.Garcia-Garcia@lboro.ac.uk

* Correspondence: joanne.gould@nottingham.ac.uk; Tel.: +44-115-951-6134

Academic Editors: To Ngai and Syuji Fujii
Received: 9 August 2016; Accepted: 14 September 2016; Published: 21 September 2016

Abstract: In this paper, we demonstrate the functionality and functionalisation of waste particles as an emulsifier for oil-in-water (o/w) and water-in-oil (w/o) emulsions. Ground coffee waste was chosen as a candidate waste material due to its naturally high content of lignin, a chemical component imparting emulsifying ability. The waste coffee particles readily stabilised o/w emulsions and following hydrothermal treatment adapted from the bioenergy field they also stabilised w/o emulsions. The hydrothermal treatment relocated the lignin component of the cell walls within the coffee particles onto the particle surface thereby increasing the surface hydrophobicity of the particles as demonstrated by an emulsion assay. Emulsion droplet sizes were comparable to those found in processed foods in the case of hydrophilic waste coffee particles stabilizing o/w emulsions. These emulsions were stable against coalescence for at least 12 weeks, flocculated but stable against coalescence in shear and stable to pasteurisation conditions (10 min at 80 °C). Emulsion droplet size was also insensitive to pH of the aqueous phase during preparation (pH 3–pH 9). Stable against coalescence, the water droplets in w/o emulsions prepared with hydrothermally treated waste coffee particles were considerably larger and microscopic examination showed evidence of arrested coalescence indicative of particle jamming at the surface of the emulsion droplets. Refinement of the hydrothermal treatment and broadening out to other lignin-rich plant or plant based food waste material are promising routes to bring closer the development of commercially relevant lignin based food Pickering particles applicable to emulsion based processed foods ranging from fat continuous spreads and fillings to salad dressings.

Keywords: pickering emulsions; particles; lignin; food emulsions

1. Introduction

Pickering particles are solid particles capable of stabilising an emulsion by the adsorption of solid particles to the oil/water interface. The application of Pickering particles has attracted significant research interest in recent years as unlike molecular emulsifiers, which constantly adsorb and desorb from the interface promoting emulsion droplet coalescence, Pickering particles are considered to be irreversibly adsorbed. This is because the free energy needed for spontaneous desorption of particles from the interface is extremely large compared to that of thermal energy. For example, for desorption of a particle of radius 10 nm adsorbed at a toluene-water interface with a contact angle of 90° the energy required is 2750 KT [1]. The particle is therefore considered to be permanently adsorbed as the high desorption energy means a high energy input is needed to disrupt the particle layers to allow droplet coalescence to occur. This holds true for all particle stabilised emulsions even for small nanoparticles ($r \approx 5$–10 nm) as long as the contact angle of the particle is not too close to 0° or 180° [2].

The properties of particle stabilised emulsions (droplet size, flocculation, viscosity) are majorly influenced by the properties of the particles and emulsion phases controlling the arrangement of the particles at the interface. Particle wettability is a key determinant of whether an oil-in-water (o/w) or a water-in-oil (w/o) emulsion is obtained, commonly characterised by the contact angle at the interface measured through the water phase. Particles classed as hydrophilic adopt a contact angle of less than 90° at a planar air/water or oil/water interface, i.e., these are preferentially wetted by water. Conversely, particles forming contact angles of greater than 90° are hydrophobic and are wetted by the oil phase to a greater extent [3,4]. During emulsion formation, the interface of a droplet will curve to ensure the larger area of the particle surface remains on the external side, such that hydrophilic particles will give rise to o/w emulsions and hydrophobic particles to w/o emulsions [3,4].

Utilisation of Pickering particles in emulsion based foods and other consumer good products, e.g., creams and lotions, offers several advantages such as replacement of artificial surfactants, prolonged shelf life, and stabilisation of complex structures such as multiple emulsions. However, the inclusion of these particles in food products is hampered through the lack of interfacially active food particles. Hydrophobic OSA modified starches [5], flavonoids [6], chitin nanocrystals extracted from crab shells [7], fat particles such as hardened rapeseed oil particles [8], protein based particles [9], protein microgels [10], egg yolk granules [11], and colloidal cellulose based fibers [12] have all been shown to have interfacial functionality although most often chemical modification is required before use. We have, on the other hand, recently demonstrated that particles from the shell and nib of the Theobroma Cacao pod act as Pickering particles. O/W emulsions readily formed during high shear mixing processes showed no evidence of a change in emulsion droplet size over 100 days of storage or the presence of an oil layer after storage for two years, indicating the formation of a highly stable microstructure [13,14]. These particles are not only food grade but also natural as there is no requirement for chemical modification. Further investigations of these natural Pickering particles indicated that the emulsifying ability of the particles was enhanced by the presence of lignin.

Lignin is the second most abundant natural polymer after cellulose, characterised by its highly branched heterogeneous structure built from aromatic residues. It is widely considered to be a hydrophobic molecule, however it has also been shown to have hydrophilic, hydrophobic, and amphiphilic character depending on botanical origin and extraction methods [15,16]. Kraft lignins [17,18], lignosulfonates [18], lignin obtained from enzymatic hydrolysis [19] and lignin microparticles [20,21] have been shown to stabilise o/w emulsions. Several methods have been used to create lignin microparticles; one such method uses aqueous ethanol to extract lignin from shrub willow and an anti-solvent precipitation protocol to prepare the microparticles. The emulsifying ability of the lignin microparticles was then assessed in a soybean oil-in-water system with the result being the formation of stable o/w emulsions with no significant change in droplet size over a storage period of five months [20].

To the best of our knowledge there have yet to be published reports on the preparation of lignin based Pickering particles for the application in w/o emulsions warranting microstructure stability. We hypothesise that a lignin rich particulate material can be suitably processed to show functionality in this system, a functionality that we were not able to impart to cocoa particles. Their lignin content of between 4% and 9% (wt/wt) [22] is either too low or the modification methods explored in this research are not suitable. Here we selected ground coffee waste with a reported lignin content of between 20% and 27% (wt/wt) [23]. It is in plentiful supply with UK coffee shops and households producing more than 500,000 tonnes [24] and 60,379 tonnes [25] of this type of waste per year respectively. However, we foresee the waste produced during the manufacture of instant coffee, termed spent coffee grounds, also to be a suitable waste stream. Application of this technology to spent coffee grounds provides an even larger commercial potential as from the 2.5 million tonnes of coffee products manufactured in Europe in 2013, 326,320 tonnes correspond to instant coffee, with a monetary value close to €3 billion [26]. This large scale production generates over 300,000 tonnes of dry spent coffee grounds every year [27].

In order to prepare these Pickering particles we have utilised a hydrothermal treatment common to the bioenergy industry with the aim of relocating the lignin to the surface of the waste coffee particles. In doing so, we expect to increase the hydrophobicity of the particle allowing stabilisation of w/o emulsion in addition to the untreated particles stabilizing o/w emulsions. The hydrothermal treatment is carried out in water at high temperatures and pressures which causes the cell wall to be disrupted and the formation of spherical droplets on the surface of the material which are understood to be largely composed of lignin [28]. Although, lignin is notoriously complex to characterize [29] multiple techniques such as FT-IR, NMR, antibody labelling, TEM, and cytochemical staining have been used to investigate the composition of the droplets, all of which determined the droplets to be composed of lignin [30,31]. The formation of droplets occurs because, at temperatures above the melting point of lignin, typically between 100 °C and 170 °C [32], lignin fluidizes, coalesces, and has the ability to move through the cell wall matrix. Once at the surface of the sample material, the hydrophobic lignin minimizes contact with the hydrophilic solvent by forming droplets which solidify once the temperature has been brought down sufficiently [32,33]. However, some authors do conclude that, during steam explosion and dilute acid treatments. Hemicellulose and lignin degradation products combine to form lignin like droplets termed pseudo-lignin [34]. Pseudo-lignin is also considered to be hydrophobic like lignin [31,35].

In this paper, we demonstrate that particles prepared from ground coffee waste show promise to be successfully applied as a versatile Pickering emulsifier through hydrothermal processing. To the best of our knowledge, this is the first report of a natural non-fat based Pickering particle suitable for application as an emulsifier of w/o food emulsions. Data presented include size, hydrophobicity, and emulsifying ability for untreated and treated ground waste coffee particles. For the sake of brevity, ground coffee waste particles are in the following referred to as coffee particles or simply particles.

2. Results and Discussion

2.1. Properties of Prepared Coffee Pickering Particles

2.1.1. Surface Morphology

The surface morphology of a coffee particle following drying after collection (Figure 1A), that was then milled (B) and additionally submitted to hydrothermal treatment at various temperatures (Figure 1C–F) as assessed using SEM is depicted in Figure 1. The untreated coffee particle shown in Figure 1A is characterised by an irregular surface with folded rounded features. Ball milling of these particles had little effect on the surface morphology of the particles except a slight smoothing of the surface as shown in Figure 1B.

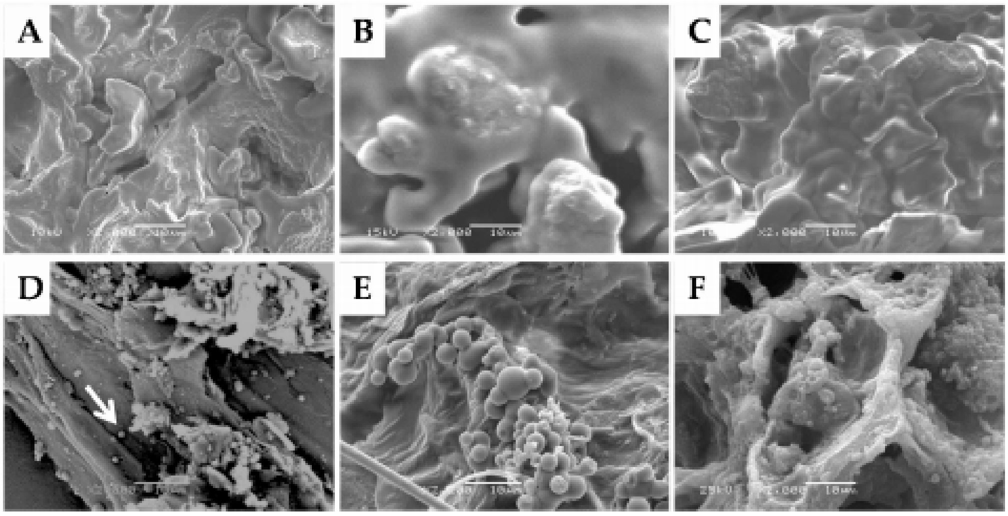


Figure 1. SEM images of **(A)** dried coffee particle; **(B)** dried and ball milled coffee particle and **(C–F)** following hydrothermal treatment at **(C)** 150 °C; **(D)** 200 °C; **(E)** 250 °C; and **(F)** 275 °C for 1 h. Scale bar represents 10 μm.

Treating the coffee particles hydrothermally at temperatures between 150 °C and 275 °C for 1 h caused the formation of droplets on the particles' surface, which was a result of the melting and relocation of the lignin component, as discussed in the introduction. By relocating the lignin in this manner, we predict the surface hydrophobicity of the coffee particles will increase enabling the stabilisation of w/o emulsions. The effect of temperature was therefore investigated to optimize the formation of these droplets on the surface, as it has previously been reported that the density of coalesced lignin located on the cell structure of hydrothermally treated sugarcane bagasse increased with temperature [36].

Figure 1D–F demonstrate that the droplets on the surface of the coffee particles appear in clusters. Clustering around and within specific structural features such as pits, cell corners, and delamination layers has previously been reported after hydrothermal treatment of corn stem rind and explained by the porosity of these areas [30]. The pores act as extrusion channels for the melted lignin. If lignin droplets were to be found more evenly distributed across the particle surface, as has been reported for hydrothermally treated sugarcane bagasse, this would be the sign of a porous ultrastructure which may be generated in situ during hydrothermal processing due to the removal and hydrolysis of lignin and hemicellulose, respectively [36].

The amount of droplets formed on the particle surface as judged by the SEM images depended on the temperature of the hydrothermal treatment (Figure 1C–F). While the SEM image 1(C) acquired after treatment at 150 °C featured no droplets, Figure 1D indicates that hydrothermal treatment at 200 °C led to the formation of a small number of small droplets with diameters of around 1 μm. Evidenced in Figure 1E, more droplets and varying in size between 2.5 μm and 5 μm formed following treatment at 250 °C. Some droplets appear to have fused together. Also recognisable are flattened edges where a droplet may have been in close contact with another droplet that was subsequently pulled off during preparation of the sample for imaging. Similar droplet features were found on the surface of corn stover rind following hydrothermal and acid treatment [30]. Figure 1F then demonstrates that further increase in temperature is detrimental to the occurrence of surface adsorbed lignin droplets. This observation suggests that there is an optimal processing temperature to impart surface hydrophobicity to coffee particles should this indeed be the functionality of what is assumed to be mostly redistributed lignin. Therefore, the sample treated at 250 °C for 1 h was selected for further investigations.

2.1.2. Lignin Content

The concentration of lignin in the particles prepared from ground coffee waste was quantified spectrophotometrically following acetyl bromide and dioxane extraction. Lignin content was 17.9% ± 1.2% in milled particles and 29.9% ± 1.2% in hydrothermally treated milled particles (250 °C for 1 h). Lignin was not created nor lost during the hydrothermal process, instead the increase in lignin content is an effect of sample mass loss due to the hydrolysis of the indigenous polysaccharides xylan and hemicellulose during hydrothermal treatment [37,38]. Such an increase has previously been reported for wheat straw following steam explosion treatment [39].

2.1.3. Particle Size

The particle size of the coffee Pickering particles is shown in Table 1 as the volume weighted mean diameter, $d_{4,3}$, and as a measure of the fine fraction the diameter below which 10% of the particles are found, $d_{10,3}$. Ball milling decreased the values of both characteristic diameters. The hydrothermal treatment appeared to slightly increase in the mean diameter which would be the result of particle aggregation during the processing. Hydrothermal treatment did not affect the size of the fine fraction which is worth noting since our previous research on the emulsifying ability of cocoa particles has shown that the size of the fine fraction dictated the diameter of the o/w emulsions processed with these particles [13]. For a new Pickering particle system as under investigation here one would base any expectation on emulsion droplet size on the mean particle diameter. The linear relationship between emulsion droplet diameter and particle diameter stabilising the interface [40] suggests that the milled and hydrothermally treated particles would stabilise smaller emulsion droplets than the unmilled coffee particles.

Table 1. Volume-weighted characteristic particle sizes of coffee particles examined for Pickering properties. All particles were dried prior to particle size analysis.

Sample	$d_{4,3}$ (μm)	$d_{10,3}$ (μm)
Unmilled	341.11 ± 21.67	35.91 ± 5.65
Milled	117.12 ± 16.15	21.90 ± 2.55
Milled and Hydrothermally Treated	144.25 ± 6.14	19.24 ± 0.20

2.1.4. Particle Hydrophobicity

The hydrophobicity of the Pickering particles was evaluated using an emulsion assay, as measuring the contact angle, the material property commonly chosen to characterise the hydrophobicity of Pickering particles—of particles with irregular shapes—can introduce significant errors, depending on the method of assessment. Instead, the emulsion composition and processing protocol described in 3.3 was designed to give an insight into the hydrophobicity of the particles, based on the type of emulsion formed.

Unmilled and milled coffee particles stabilised o/w emulsions regardless of the oil phase composition (polarity) which was confirmed with the drop test where all emulsions dispersed in water rather than in a sample of the oil phase of the emulsion. The stabilisation of o/w emulsions by these Pickering particles indicates their hydrophilic nature, as even with the most polar oil phase (100% IPM) o/w emulsions were formed.

Figure 2 shows the microstructures of a selection of the o/w emulsions stabilised by unmilled (Figure 2A–C) and milled coffee particles (Figure 2D–F). The micrographs show that the Pickering emulsions have a flocculated microstructure and the milling of the particles enabled the stabilisation of smaller droplets, in accordance with the smaller particle size of the milled sample reported in Table 1. Oil droplets stabilised by unmilled coffee particles showed a broad size distribution which makes differentiating the effect of oil polarity on emulsification efficacy difficult. In contrast, the size of emulsion droplets stabilised by milled coffee particles was affected by the oil phase polarity, with larger droplets stabilised when the oil phase consisted of equal quantities of IPM and dodecane as evident in Figure 2E. In absence of experimental evidence, we suggest that the altered interfacial properties or viscosity properties of the oil phase may be the reason for the formation of the larger droplets.

In contrast, emulsions processed in the presence of hydrothermally treated coffee particles formed w/o emulsions regardless of the polarity of the oil phase, again confirmed by the result of the drop test where all emulsions dispersed in the oil phase. This result demonstrates that hydrothermal treatment increased the hydrophobicity of the particles most likely due to the relocation of lignin to the particle surface.

Figure 3 shows the microstructures of the different w/o emulsions (varying oil phase polarity) stabilised by milled and hydrothermally treated coffee particles. Comparison of Figure 3 to Figure 2 reveals obvious microstructure differences. The droplet size in the w/o emulsions was considerably larger than the droplet size in the o/w emulsions featuring droplets with diameter of between 100 μm and 300 μm. Another difference is the occurrence of irregular shaped water droplets, pointed out by the arrows in Figure 3B–E, as an intermediate stage of coalescence—termed arrested coalescence—in which droplets retain the shape of the original droplets to some extent. Complete coalescence is halted when the interface is jammed with particles preventing further reduction in interfacial area to a spherical droplet. This phenomenon is therefore strongly dependent on the level of droplet surface coverage with particles [41]. A high degree of droplet surface coverage with particles (Ø = 0.9) creates a closely packed jammed interfacial layer preventing total coalescence. In the emulsions shown in Figure 3, the droplets are described as in state of arrested coalescence. At lower surface coverage and if the combined particle covered surface area of two droplets exceeds the interfacial area that would form by complete coalescence arrested coalescence will occur. Based on experimental data, it was deducted that a combined intermediate particle surface coverage of the two droplets of $1.43 < Ø_1 + Ø_2 < 1.81$ is required to prevent total coalescence, leaving droplets in an arrested state of coalescence [41]. The presence of irregular shaped water droplets in the case of hydrothermally treated coffee Pickering particles therefore indicates an intermediate level of water droplet surface coverage with these coffee particles.

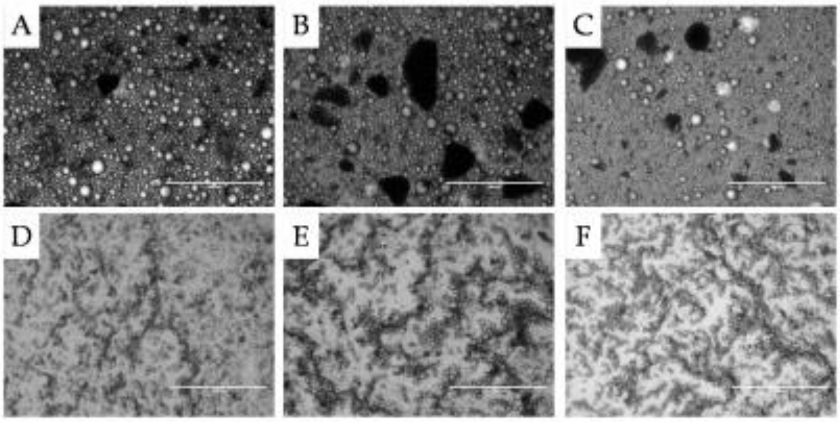


Figure 2. Light micrographs of o/w emulsions with 46% oil and stabilised with 8% unmilled or milled coffee particles with different oil phase polarity acquired after one day of storage at 25 °C. Images are as follows; unmilled coffee particle with an oil phase of (**A**) 100% dodecane (least polar); (**B**) 50% dodecane and 50% IPM (intermediate polarity) and (**C**) 100% IPM (most polar) and milled coffee particles (**D**) 100% dodecane; (**E**) 50% dodecane and 50% IPM and (**F**) 100% IPM. Scale bar represents 1000 μm.

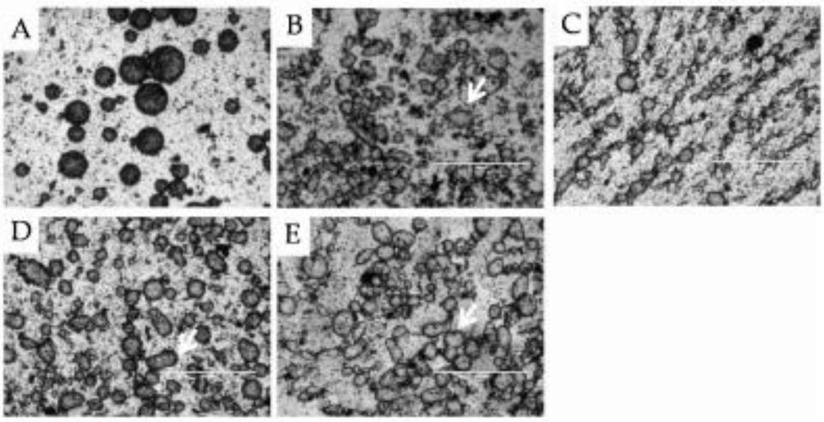


Figure 3. Light micrographs of w/o emulsions with 46% water and stabilised with 8% hydrothermally treated coffee particles with differing oil phase composition acquired after one day of storage at 25 °C. Images are of w/o emulsions with oil phases of (**A**) 100% dodecane; (**B**) 75% dodecane; (**C**) 50% dodecane; (**D**) 25% dodecane; and (**E**) 100% IPM. Scale bar represents 1000 μm. The arrows indicate the presence of arrested coalescence.

This intermediate surface coverage may be the result of the heterogeneous distribution of lignin droplets on the particle surface evidenced in Figure 1. These overall hydrophobic Pickering particles are characterised by inhomogeneous surface chemistry, and adsorption onto the water droplet surface appears to be possible only for the more hydrophilic or lignin-poor surface domains. Particle adsorption therefore maybe characterised by large parts of the particles residing in the water phase resulting in a lower surface coverage and causing the larger size of the stabilised droplets compared to the o/w emulsions with untreated particles of a most likely relatively homogenous surface chemistry. Optimisation of the hydrothermal treatment may allow a more homogenous or control over surface chemistry/hydrophobicity allowing an increase in particle adsorption to the interface and therefore an increased surface coverage by particles, preventing arrested coalescence of emulsion droplets.

2.2. Application of Coffee Pickering Particles in Food Emulsions

The processability of o/w emulsions stabilised with milled waste coffee Pickering particles was evaluated to see whether coffee Pickering particles could be successfully incorporated into manufactured food products. The processability and storage stability of these Pickering emulsions was evaluated in a food emulsion formulation consisting of 46% sunflower oil and by subjecting the emulsions to shearing and heating as well as acidic and alkaline conditions. W/O emulsions were not characterised in terms of processability as the large size of the water droplets stabilised by hydrothermally treated waste coffee particles are not currently desirable in food products due to their predictable instability towards shear and mixing processes as well as potentially imparting a rough mouthfeel as the water droplets may be sensed as large solid particles due to the arrested nature of the interface.

2.2.1. Microstructure Stability

Figure 4 shows the size distribution of o/w emulsions stabilised by milled waste coffee particles measured after 1 day, 6 weeks, and 12 weeks of storage at 25 °C, alongside the size distribution of an aqueous dispersion of the milled waste coffee particles. The emulsion had a bimodal distribution with sharp peaks at 100 μm and 500 μm. It is also evident that there was a significant overlap between the size distribution of the emulsion droplets and the particles that stabilise the emulsion droplets. Based on the microscopy evidence shown in Figure 5A the peak at 100 μm can be assigned to the emulsion droplets. Due to conclusions from previous literature [2], we expect the particles that stabilise the emulsion droplets to be in the order of one magnitude smaller in diameter which would correspond to the distribution of particles below 10 μm. Particle sizes around 500 μm identify particle aggregates that can be noted in Figure 5A or individual very large particles having a large impact on particle size distribution due to weighting by volume. It is also worth noting that the difference between the emulsion and dispersion distributions between 10 μm and 30 μm is indicative of the presence of unadsorbed suspended particles in the emulsion.

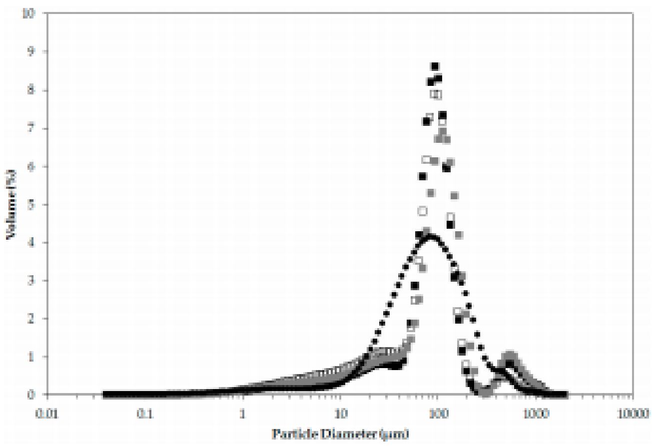


Figure 4. Emulsion droplet diameter volume size distribution of o/w emulsions stabilised with 8% milled waste coffee Pickering particles and sunflower oil as the oil phase (46%) acquired after 1 day (■), 6 weeks (□), and 12 weeks (■) of storage at 25 °C, is presented alongside the size distribution of the particles (●) Data presented is the mean distribution of three independent emulsion samples.

As shown in Figure 4, the peak at 100 μm remained constant over the studied storage period of 12 weeks and there was no significant change in the mean diameter over storage as can be seen in Figure 7. There were minor changes in the volume fraction of the larger particles (peak around 500 μm) which we expect to be due to sampling of the large particle aggregates or individual large particles.

2.2.2. Temperature Stability

To ensure products are safe for consumption high temperature processing steps such as pasteurisation, sterilisation, and cooking are often used in food manufacturing. It was therefore important to investigate the influence of heating and holding the emulsion at 80 °C for 10 min on the emulsion microstructure. Figure 5A,B presents the microstructure before and after heating, respectively. There is little difference in the degree of flocculation and droplet size evident, which was reflected in the results of the particle size analysis on these two samples (data not presented). The heat stability of the coffee particle Pickering system indicates that these emulsions could be utilised in thermally processed foods.

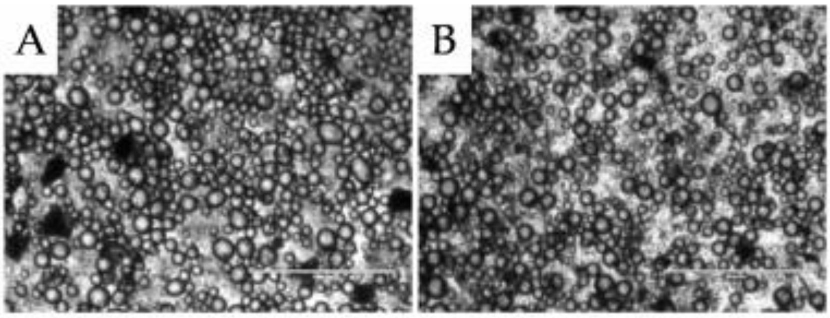


Figure 5. Light micrographs of o/w emulsions stabilised with 8% milled waste coffee Pickering particles and sunflower oil as the oil phase (46%) before heating (**A**); and after heating (**B**) the emulsion to 80 °C. Scale bar represents 1000 μm.

2.2.3. Shear Stability

In addition to storage and temperature stability, the microstructure of the coffee particle stabilised emulsions showed good shear stability as shown in Figure 6. The viscosity data were acquired by increasing and then decreasing the shear rate which was repeated three times in total. The emulsion is clearly shear thinning and the slight shoulder between 1 s^{-1} and 10 s^{-1} indicates that some slip occurred. Nevertheless, following the first attainment of the highest shear rate, the viscosity data overlapped at each shear rate and the viscosity recorded at the highest shear rate was constant independent of the step in the measurement sequence. This behaviour is highly indicative of the equilibration of the emulsion's superstructure during the first shear rate increase in response to the shear rate applied, thus viscosity subsequently probed at a shear rate lower or equal to this maximum shear rate remained unchanged. There was no evidence of droplet break up caused by the shearing protocol as the mean size, characterised by the $d_{4,3}$, of the emulsion droplets was not significantly ($p < 0.05$) different in emulsions before and after shearing (data not shown). Typically, it is flocculation of emulsion droplets and in this case potentially also of aggregates of non-adsorbed coffee particles that are broken up during the first shear rate increase in such up and down shear rate protocols. Indeed, the emulsion as shown in Figure 5A appears slightly flocculated.

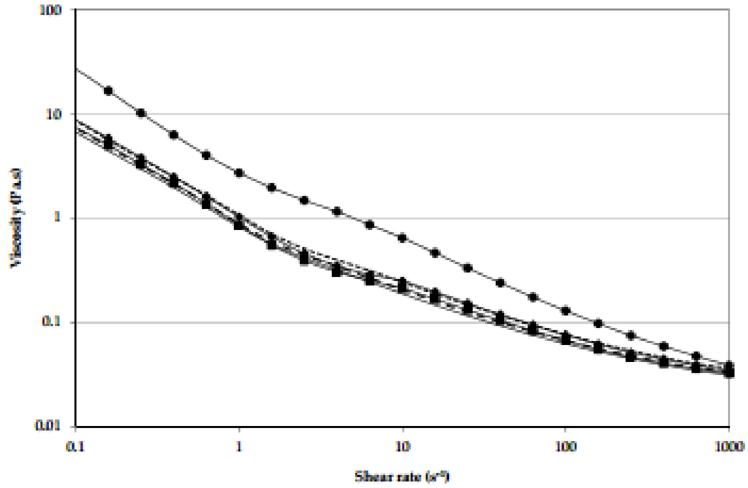


Figure 6. Shear stability was evaluated by applying a shear rate increase to 1000 s^{-1} and decrease to 0 s^{-1}, the protocol was repeated a total of three times. Black symbols indicate shear increase steps (1st●, 2nd⧫, and 3rd■) and straight lines represent shear decrease steps (1st·········, 2nd– – –, and 3rd———).

2.2.4. pH Stability of Milled Waste Coffee Pickering Emulsions

Application in manufactured foods will expose the emulsions to a range of ingredients including acids and alkalis. In order to assess whether these changes could cause emulsion destabilisation, aqueous phases were adjusted to pH 3, 6, and 9 prior to homogenisation and the stability of the emulsions formed were assessed. Figure 7 shows the volume mean emulsion droplet diameters of the pH adjusted emulsions after one day and four weeks of storage alongside data acquired on an emulsion formed with pure water as the aqueous phase. Altering the pH of the aqueous phase between 3 and 9 did not have a significant effect on the mean emulsion droplet size over the storage period.

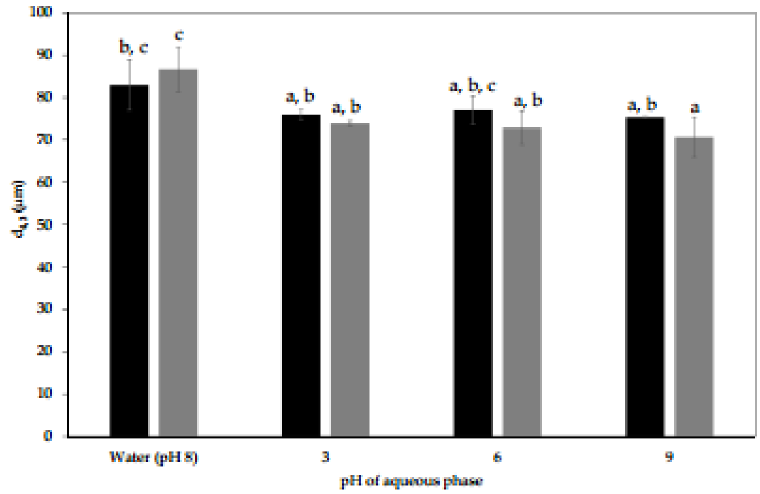


Figure 7. Volume mean emulsion droplet diameter acquired one day (■) and four weeks (■) after emulsification. The emulsions were formed with aqueous phases adjusted to pH 3, 6, 9. The droplet size of emulsions formed with pure water (pH 8) as the aqueous phase was included this data was acquired after one day (■) and six weeks (■). Emulsion formulation contained 8% milled waste coffee Pickering particles and 46% sunflower oil. The presence of different letters (a,b,c) represent a significant difference between samples ($p < 0.05$).

3. Materials and Methods

3.1. Materials

Ground coffee waste produced from a variety of ground coffee products was collected from a local coffee outlet. Sodium azide (Sigma-Aldrich, Dorset, UK) was added as antimicrobial agent to all aqueous emulsion phases to give a final concentration of 0.02% w/w. Double distilled water was used for all samples. The oil phase of the emulsions varied in composition of isopropyl myristate (IPM) and dodecane (Sigma-Aldrich, Dorset, UK) and commercially available sunflower oil (purchased at a local supermarket). Acetyl bromide (Sigma-Aldrich, Dorset, UK), glacial acetic acid (Fisher Scientific, Loughborough, UK), and low sulfonate kraft lignin (Sigma-Aldrich, Dorset, UK) were used to quantify the lignin content of the milled ground coffee waste particles and hydrothermally treated ground coffee waste particles. Hydrochloric acid (SG 1.16, 32%) (HCl) (Fisher Scientific, Loughborough, UK) and sodium hydroxide pellets (NaOH) (Fisher Scientific, Loughborough, UK) were used to adjust the pH of the aqueous phase to pH 3, 6, and 9. All of these materials were used as received.

3.2. Prepartation of Ground Coffee Waste Particle Preparation

Pickering particles were prepared from this material after drying in a convection oven at 40 °C for 48 h to a moisture content of 7.3% ± 0.2% and milling by dry grinding in a planetary ball mill (PULVERISETTE 5 classic line, Fritsch GmbH, Oberstein, Germany) for particle size reduction. The milling conditions were 10 zirconium oxide (ZrO_2) balls 15 mm in diameter and 70 g of ground coffee waste particles in a 500 mL ZrO_2 grinding bowl at a main disc speed setting of 200 rpm for 12 h. The milling programme consisted of 5 min intervals of milling and no milling to minimize heat production. Hydrothermally treated milled ground coffee waste particles were prepared by hydrothermally treating the milled waste coffee particles using a protocol adapted from literature [24]. 4 g of sample was mixed with 40 ml of water and sealed into stainless steel tubular reactors (17 cm long and 3 cm inner diameter). Loaded reactors were held at selected temperatures between 150 °C and 275 °C for 1 h. At the conclusion of the treatment, the tubes were cooled by submerging in cold water for 5 min. Solids were retained by filtration (Whatman Grade 1, Kent, UK) and dried in a convection oven at 40 °C for 48 h to a final moisture content of 5.5% ± 0.1%.

3.3. Emulsion Processing

All emulsions regardless of the components were prepared as follows. Emulsions were produced on a 50 g scale, containing 46% oil, 46% double distilled water, and 8% particles, based on preliminary experiments (data not presented) where it was found that emulsions containing less than 8% particles were unstable to coalescence. Particles were added as a powder on top of the water phase (the densest liquid phase) followed by the oil phase, in accordance with the powdered particle method [42] as this removes any effect of the initial location of the particles on their wettability which could influence the type of emulsion formed (o/w or w/o). The mixture was emulsified using a high shear overhead mixer (L5M Series fitted with emulsor screen, Silverson, Chesham, UK) operating at 9000 rpm for 2 min. The emulsion type was confirmed by observing whether a drop of the emulsion dispersed in pure oil or in pure water, with a w/o emulsion dispersing in oil and an o/w emulsion dispersing in water [42].

3.4. Characterisation of Ground Coffee Waste Pickering Particles and Pickering Emulsions

3.4.1. Lignin Quantification

The milled ground coffee waste and hydrothermally treated (250 °C, 1 h) coffee waste particles' lignin content was quantified by initially extracting the lignin using acetyl bromide followed by measurement of absorbance (UV-Vis Spectrophotometer, Varian Cary 50, Agilent Technologies, Santa Clara, CA, USA) at 280 nm [24]. Briefly, 100 mg of sample material was dissolved in 4 mL of solvent (25% acetyl bromide, 75% glacial acetic acid) followed by incubation at 50 °C for 2 h. Quantification was performed by calibration using the low sulphonate kraft lignin as a reference material.

3.4.2. Microstructure Imaging

The surface structure of the untreated, milled and hydrothermally treated ground coffee waste particles was investigated using SEM (JSM 6060LV, JEOL, Tokyo, Japan). The particles were placed on SEM stubs with carbotape followed by drying under vacuum before being coated in gold using gold splutter (Leica SCD 0005, Leica Microsystems, Milton Keynes, UK). The samples were then transferred to the SEM stage for imaging.

The microstructure of emulsions was visualised utilizing bright field microscopy (EVOS f1, AMG, Washington, DC, USA) with the aim to support particle sizing data for water continuous emulsions. In the case of oil-continuous emulsions, bright field microscopy was the only method applied to get an insight into droplet size.

3.4.3. Particle Sizing

Size distributions for the aqueous suspensions of waste coffee particles and oil-in-water emulsions were acquired with a low angle laser diffraction particle size analyser (LS 13 320, Beckman Coulter, High Wycombe, UK) fitted with a dispersion cell filled with water (Universal liquid module, LS13 320, Beckman Coulter, High Wycombe, UK). Three independent replicates of each sample were taken. Data was analysed using the Fraunhofer diffraction model using the instrument's software. Oil-continuous emulsions were not analysed in this equipment due to the reported shear sensitivity of these emulsions and potential droplet size reduction due to the mixing and pumping processes in the dispersion cell.

3.4.4. Particle Hydrophobicity

Particle hydrophobicity was evaluated through an emulsion assay where the lipophilic emulsion phase is varied in polarity and water is the hydrophilic emulsion phase. Following the emulsion preparation method described in 3.3 removing volume fraction of either emulsion phase and initial location of particle addition as impacting factors, the type of emulsion formed provides an indication of particle hydrophobicity as the particles will transfer into the continuous emulsion phase during emulsification, with hydrophilic particles stabilising an o/w emulsion and hydrophobic particles stabilising a w/o emulsion. The polarity of the oil phase was altered to contain varying quantities (0%, 25%, 50%, 75%, and 100%) of IPM, a polar oil, and dodecane, a non-polar oil, as it has been shown in emulsions stabilised with silica particles of intermediate hydrophobicity the nature of the oil can affect the final type of the emulsion formed. Binks et al. [43] found that a polar oil e.g., IPM, interacts more strongly with water; the strength of the interaction can be quantified in terms of the work of adhesion and is calculated from the interfacial tension of the system. As the adhesion between the phases increases, due to an increase in polarity, the water fraction at which phase inversion also increases, therefore for the most polar oils the work of adhesion is too high so no phase inversion occurs allowing only w/o emulsions to be formed whereas non-polar oils preferentially form o/w emulsions. However, as we will show, the hydrophobicity of the Pickering particles can overrule this affect.

3.4.5. Process Stability of o/w Emulsions

To evaluate whether o/w emulsions stabilised by milled ground coffee waste Pickering particles could be successfully incorporated into manufactured food products, sunflower oil-in-water emulsions stabilised with milled ground coffee waste particles were subjected to shear and heat as well as acidic and alkaline conditions as relevant to process steps such as mixing, pumping, pasteurisation, and pH adjustment to achieve desired product textures or to contribute to microbial stability of the product.

The shear stability of the emulsions was evaluated at 20 °C using a rotational rheometer (MCR301, Anton Paar, Graz, Austria) fitted with a concentric cylinder geometry (bob diameter: 27 mm, bob length: 40 mm, cup diameter: 29 mm) applying the following shear ramp protocol. The shear rate was increased from 0.1 to 1000 s^{-1} in 5 min followed by a shear rate decrease from 1000 to 0.1 s^{-1} in 5 min. The shear ramp was repeated three times with the viscosity recorded and plotted against shear rate for all shear ramps.

The influence of temperature on emulsion stability was examined by placing the emulsions in individual glass vials followed by incubation in a water bath at 80 °C for 10 min. The pH of the aqueous phases of the emulsions were adjusted to pH 3, 6, and 9 by adding either HCl or NaOH prior to emulsification. The stability of emulsions subjected to high temperature or different pH environments was evaluated by assessing changes to droplet size and microstructure of the emulsions. Due to the presence of particle aggregates and potentially individual large particles, the particle size data were manipulated to remove any data at sizes greater than 400 μm, therefore only changes to the emulsion droplet size could be assessed.

3.5. Statistical Analysis

Mean size and standard deviation are reported based on three independent samples. The particle size data was significantly analysed using an ANOVA and Tukey's statistical test with the level of significance set at $p = 0.05$ for both statistical tests.

4. Conclusions

Waste coffee particles (unmilled and milled) and hydrothermally treated waste coffee particles can act as Pickering particles for both o/w and w/o emulsions. The Pickering stabilisation is a result of the presence and, for w/o application the relocation of the known emulsifying agent, lignin. Pickering particle hydrophobicity assessment confirmed that the relocation of the lignin to the particle surface had increased the hydrophobicity of the particles compared to the hydrophilic untreated particles. However, emulsions stabilised with the hydrothermally treated waste coffee Pickering particles had large droplets which would not be suitable for incorporation into food products, necessitating further research into process optimisation for this application.

On the other hand, the use of milled waste coffee Pickering particles to stabilise o/w emulsions of typical food formulation produced emulsion droplets of desirable size with no change in microstructure seen over a period of 12 weeks of storage. Investigations also showed that the o/w emulsions to be stable to shearing up to 1000 s^{-1} and heating to 80 °C, conditions typical of food product manufacture. Finally, altering the pH of the aqueous phase to between pH 3 and pH 9 was not found not to affect the stability of the emulsions with no change in droplet size seen for a period of four weeks.

Overall, this study has demonstrated that lignin rich food waste can be functionalised as a food ingredient with emulsifying property for both oil and water based foods. While application in water based foods, i.e., for o/w emulsions, appears to be more readily possible and is thus potentially closer to application, further research is required to develop commercially relevant particles for the application in lipid continuous foods or for the stabilisation of the encapsulated water phase in duplex (w/o/w) food emulsions. In addition, the natural abundance of lignin in plant based materials and plant based food waste begs to extend this application to materials other than coffee. Due to the complex and variable structure of lignin, the use of different sources could enable the creation of particles with a range of functionalities and applications.

Acknowledgments: This research was funded through the EPSRC Centre for Innovative Manufacturing in Food grant (EP/K030957/1). We would like to thank Christine Grainger-Boultby, Khat Husain, and Roger Ibbett for technical support.

Author Contributions: J.G. and B.W. conceived the research project and designed experiments. J.G. carried out all experiments. G.G.G. reviewed the literature on waste coffee. J.G. drafted the manuscript; B.W. supervised its preparation; all authors were involved in revising it. All authors have approved and are accountable for the final version of the manuscript submitted.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

References

1. Binks, B.P. Particles as surfactants-similarities and differences. *Curr. Opin. Coll. Interface Sci.* **2002**, *7*, 21–41. [CrossRef]
2. Dickinson, E. Use of nanoparticles and microparticles in the formation and stabilization of food emulsions. *Trends Food Sci. Technol.* **2012**, *24*, 4–12. [CrossRef]
3. Aveyard, R.; Binks, B.P.; Clint, J.H. Emulsions stabilised solely by colloidal particles. *Adv. Colloid Interface Sci.* **2003**, *100*, 503–546. [CrossRef]
4. Finkle, P.; Draper, H.D.; Hildebrand, J.H. The theory of emulsification. *J. Am. Chem. Soc.* **1923**, *45*, 2780–2788. [CrossRef]
5. Yusoff, A.; Murray, B.S. Modified starch granules as particle-stabilizers of oil-in-water emulsions. *Food Hydrocoll.* **2011**, *25*, 42–55. [CrossRef]
6. Luo, Z.J.; Murray, B.S.; Yusoff, A.; Morgan, M.R.A.; Povey, M.J.W.; Day, A.J. Particle-stabilizing effects of flavonoids at the oil-water interface. *J. Agric. Food Chem.* **2011**, *59*, 2636–2645. [CrossRef] [PubMed]
7. Tzoumaki, M.V.; Moschakis, T.; Kiosseoglou, V.; Biliaderis, C.G. Oil-in-water emulsions stabilized by chitin nanocrystal particles. *Food Hydrocoll.* **2011**, *25*, 1521–1529. [CrossRef]
8. Paunov, V.N.; Paunov, V.N.; Cayre, O.; Nobel, P.F.; Stoyanov, S.D.; Velikov, K.P.; Golding, M. Emulsions stabilised by food colloid particles: Role of particle adsorption and wettability at the liquid interface. *J. Colloid Interface Sci.* **2007**, *312*, 381–389. [CrossRef] [PubMed]
9. De Folter, J.W.J.; van Ruijven, M.W.M.; Velikov, K.P. Oil-in-water Pickering emulsions stabilized by colloidal particles from the water-insoluble protein zein. *Soft Matter* **2012**, *8*, 2807–2815. [CrossRef]
10. Destribats, M.; Rouvet, M.; Gehin-delval, C.; Schmitt, C.; Binks, B.P. Emulsions stabilised by whey protein microgel particles: Towards food-grade Pickering emulsions. *Soft Matter* **2014**, *10*, 6941–6954. [CrossRef] [PubMed]
11. Rayner, M.; Marku, D.; Eriksson, M.; Sjöö, M.; Dejmek, P.; Wahlgren, M. Biomass-based particles for the formulation of Pickering type emulsions in food and topical applications. *Colloid Surf. A Physicochem. Eng. Appl.* **2014**, *458*, 48–62. [CrossRef]
12. Campbell, A.L.; Holt, B.L.; Stoyanov, S.D.; Paunov, V.N. Scalable fabrication of anisotropic micro-rods from food-grade materials using an in shear flow dispersion-solvent attrition technique. *J. Mater. Chem.* **2008**, *18*, 4074–4078. [CrossRef]
13. Gould, J.; Vieira, J.; Wolf, B. Cocoa particles for food emulsion stabilisation. *Food Funct.* **2013**, *4*, 1369–1375. [CrossRef] [PubMed]
14. Vieira, J.B.; Husson, J.; Wolf, B.; Gould, J. Emulsion Stabilisation. Patent EP2589297, 2013.
15. Doherty, W.O.; Mousavioun, P.; Fellows, C.M. Value-adding to cellulosic ethanol: Lignin polymers. *Ind. Crops Prod.* **2011**, *33*, 259–276. [CrossRef]
16. Tortora, M.; Cavalieri, F.; Mosesso, P.; Ciaffardini, F.; Melone, F.; Crestini, C. Ultrasound driven assembly of lignin into microcapsules for storage and delivery of hydrophobic molecules. *Biomacromolecules* **2014**, *15*, 1634–1643. [CrossRef] [PubMed]
17. Afanas'ev, N.; Selyanina, S.; Selivanova, N. Stabilization of the oleic acid-water emulsion with various kraft lignins. *Russ. J. Appl. Chem.* **2008**, *81*, 1851–1855. [CrossRef]
18. Gundersen, S.A.; Sæther, Ø.; Sjöblom, J. Salt effects on lignosulfonate and Kraft lignin stabilized O/W-emulsions studied by means of electrical conductivity and video-enhanced microscopy. *Colloid Surf. A Physicochem. Eng. Asp.* **2001**, *186*, 141–153. [CrossRef]
19. Gan, M.; Pan, J.; Zhang, Y.; Dai, X.; Yin, Y.; Qu, Q.; Yan, Y. Molecularly imprinted polymers derived from lignin-based Pickering emulsions and their selectively adsorption of lambda-cyhalothrin. *Chem. Eng. J.* **2014**, *257*, 317–327. [CrossRef]
20. Stewart, H.E. Development of Food-Grade Microparticles from Lignin. Ph.D. Thesis, Massey University, Palmerston North, New Zealand, 2015.
21. Wei, Z.; Yang, Y.; Yang, R.; Wang, C. Alkaline lignin extracted from furfural residues for pH-responsive Pickering emulsions and their recyclable polymerization. *Green Chem.* **2012**, *14*, 3230–3236. [CrossRef]
22. Redgwell, R.J.; Trovato, V.; Curti, D. Cocoa bean carbohydrates: Roasting-induced changes and polymer interactions. *Food Chem.* **2003**, *80*, 511–516. [CrossRef]

23. Pujol, D.; Gominho, J.; Olivella, M.A.; Fiol, N.; Villaescusa, I.; Pereira, H. The chemical composition of exhausted coffee waste. *Ind. Crops Prod.* **2013**, *50*, 423–429. [CrossRef]
24. Business Waste: How to Keep Coffee Grounds Out of the Ground. Avaliable online: http://www.gd-environmental.co.uk/blog/business-waste-how-keep-coffee-grounds-out-ground/ (accessed on 1 June 2016).
25. Chapagain, A.; James, K. *The Water and Carbon Footprint of Household Food and Drink Waste in the UK*; WRAP and WWF: Banbury, UK, 2011.
26. *European Coffee Report 2013/2014: European Chapter and Key National Data*; European Coffee Federation: Brussels, Belgium, 2014.
27. Obruca, S.; Benesova, P.; Kucera, D.; Petrik, S.; Marova, I. Biotechnological conversion of spent coffee grounds into polyhydroxyalkanoates and carotenoids. *New Biotechnol.* **2015**, *32*, 569–574. [CrossRef] [PubMed]
28. Pu, Y.Q.; Hu, F.; Huang, F.; Ragauskas, A.J. Lignin Structural Alterations in Thermochemical Pretreatments with Limited Delignification. *Bioenergy Res.* **2015**, *8*, 992–1003. [CrossRef]
29. Dean, J.F. Lignin analysis. In *Methods in Plant Biochemistry and Molecular Biology*, 1st ed.; CRC Press: Cleveland, OH, USA, 1997; pp. 199–215.
30. Donohoe, B.S.; Decker, S.R.; Tuvker, M.P.; Himmel, M.E.; Vinzant, T.B. Visualizing Lignin Coalescence and Migration Through Maize Cell Walls Following Thermochemical Pretreatment. *Biotechnol. Bioeng.* **2008**, *101*, 913–925. [CrossRef] [PubMed]
31. Araya, F.; Troncoso, E.; Mendonca, R.T.; Freer, J. Condensed lignin structures and re-localization achieved at high severities in autohydrolysis of Eucalyptus globulus wood and their relationship with cellulose accessibility. *Biotechnol. Bioeng.* **2015**, *112*, 1783–1791. [CrossRef] [PubMed]
32. Ma, J.; Zhang, X.; Zhou, X.; Xu, F. Revealing the Changes in Topochemical Characteristics of Poplar Cell Wall During Hydrothermal Pretreatment. *BioEnergy Res.* **2014**, *7*, 1358–1368. [CrossRef]
33. Ma, X.J.; Cao, S.L.; Luo, X.L.; Chen, L.H.; Huang, L.L. Surface characterizations of bamboo substrates treated by hot water extraction. *Bioresour. Technol.* **2013**, *136*, 757–760. [CrossRef] [PubMed]
34. Sannigrahi, P.; Kim, D.H.; Jung, S.; Ragauskas, A. Pseudo-lignin and pretreatment chemistry. *Energy Environ. Sci.* **2011**, *4*, 1306–1310. [CrossRef]
35. Hu, F.; Jung, S.; Ragauskas, A. Impact of Pseudolignin versus Dilute Acid-Pretreated Lignin on Enzymatic Hydrolysis of Cellulose. *ACS Sustain. Chem. Eng.* **2013**, *1*, 62–65. [CrossRef]
36. Reddy, P.; Lekha, P.; Reynolds, W.; Kirsch, C. Structural characterisation of pretreated solids from flow-through liquid hot water treatment of sugarcane bagasse in a fixed-bed reactor. *Bioresour. Technol.* **2015**, *183*, 259–261. [CrossRef] [PubMed]
37. Ibbett, R.; Gaddipati, S.; Greetham, D.; Hill, S.; Tucker, G. The kinetics of inhibitor production resulting from hydrothermal deconstruction of wheat straw studied using a pressurised microwave reactor. *Biotechnol. Biofuels* **2014**, *7*, 1. [CrossRef] [PubMed]
38. Ko, J.K.; Kim, Y.; Ximenes, E.; Ladisch, M.R. Effect of liquid hot water pretreatment severity on properties of hardwood lignin and enzymatic hydrolysis of cellulose. *Biotechnol. Bioeng.* **2015**, *112*, 252–262. [CrossRef] [PubMed]
39. Heiss-Blanquet, S.; Zheng, D.; Ferreira, N.L.; Lapierre, C.; Baumberger, S. Effect of pretreatment and enzymatic hydrolysis of wheat straw on cell wall composition, hydrophobicity and cellulase adsorption. *Bioresour. Technol.* **2011**, *102*, 5938–5946. [CrossRef] [PubMed]
40. Binks, B.; Lumsdon, S. Pickering emulsions stabilized by monodisperse latex particles: Effects of particle size. *Langmuir* **2001**, *17*, 4540–4547. [CrossRef]
41. Pawar, A.B.; Caggioni, M.; Ergun, R.; Hartel, R.W.; Spicer, P.T. Arrested coalescence in Pickering emulsions. *Soft Matter* **2011**, *7*, 7710–7716. [CrossRef]
42. Binks, B.P.; Fletcher, P.D.I.; Holt, B.L.; Beaussoubre, P.; Wong, K. Phase inversion of particle-stabilised perfume oil-water emulsions: Experiment and theory. *Phys. Chem. Chem. Phys.* **2010**, *12*, 11954–11966. [CrossRef] [PubMed]
43. Binks, B.P.; Lumsdon, S.O. Effects of oil type and aqueous phase composition on oil-water mixtures containing particles of intermediate hydrophobicity. *Phys. Chem. Chem. Phys.* **2000**, *2*, 2959–2967. [CrossRef]

Appendix 6: Journal paper

A Methodology for Sustainable Management of Food Waste

This paper has been published in the journal *Waste and Biomass Valorization*.

Waste Biomass Valor
DOI 10.1007/s12649-016-9720-0

ORIGINAL PAPER

A Methodology for Sustainable Management of Food Waste

Guillermo Garcia-Garcia[1] · Elliot Woolley[1] · Shahin Rahimifard[1] · James Colwill[1] · Rod White[2] · Louise Needham[3]

Received: 9 June 2016 / Accepted: 29 September 2016

Abstract As much as one-third of the food intentionally grown for human consumption is never consumed and is therefore wasted, with significant environmental, social and economic ramifications. An increasing number of publications in this area currently consider different aspects of this critical issue, and generally focus on proactive approaches to reduce food waste, or reactive solutions for more efficient waste management. In this context, this paper takes a holistic approach with the aim of achieving a better understanding of the different types of food waste, and using this knowledge to support informed decisions for more sustainable management of food waste. With this aim, existing food waste categorizations are reviewed and their usefulness are analysed. A systematic methodology to identify types of food waste through a nine-stage categorization is used in conjunction with a version of the waste hierarchy applied to food products. For each type of food waste characterized, a set of waste management alternatives are suggested in order to minimize environmental impacts and maximize social and economic benefits. This decision-support process is demonstrated for two case studies from the UK food manufacturing sector. As a result, types of food waste which could be managed in a more sustainable manner are identified and recommendations are given. The applicability of the categorisation process for industrial food waste management is discussed.

Keywords Food waste · Waste categorization · Waste management · Food sustainability · Brewery waste · Mycoprotein waste

✉ Elliot Woolley
E.B.Woolley@lboro.ac.uk

Guillermo Garcia-Garcia
G.Garcia-Garcia@lboro.ac.uk

Shahin Rahimifard
S.Rahimifard@lboro.ac.uk

James Colwill
J.A.Colwill@lboro.ac.uk

Rod White
Rod.White@molsoncoors.com

Louise Needham
Louise.Needham@quornfoods.com

[1] Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University, Loughborough, Leicestershire, UK

[2] Molson Coors, Burton-on-Trent, Staffordshire, UK

[3] Quorn Foods, Stokesley, North Yorkshire, UK

Introduction

Food waste is one of the most challenging issues humankind is currently facing worldwide. Currently, food systems are extremely inefficient: it is estimated that between one-third and one half of the food produced is lost before reaching a human mouth [1, 2]. The Sustainable Development Goal 12 'Ensure sustainable consumption and production patterns' established by the United Nations in 2015 includes a specific target for food waste reduction: halve per capita global food waste at retail and consumer levels by 2030. Additionally, it also includes a more general goal to reduce food losses along food supply chains [3]. Therefore, it is expected that there will be an increasing number of initiatives, campaigns and legislative developments in order to reach the aforementioned objectives.

Nevertheless, reduction of the current levels of food waste must be accompanied by better management of the

Published online: 25 October 2016

waste: inevitably there will always be some food waste. Furthermore, some parts of the food products are inedible and will unavoidably become a waste stream. There are countless alternatives to manage food waste, however the most common solution worldwide is still landfilling [4], which is highly damaging to the environment and poses a risk to human health, whereas it does not provide any benefit. In spite of the progress achieved in recent years to find alternative solutions, particularly in developed nations, better management of food waste in supply chains is still required.

Sustainable management of food waste is a momentous research area that has rapidly grown over recent years. Meritorious examples of research aiming to find sustainable solutions for food waste management are numerous, but they have been generally inclined to look into only one area of sustainability: environmental, economic or social ramifications [5, 6]. Recent research aims to expand the scope and consider two or even all three pillars of sustainability implications mentioned above. Remarkable examples are work by Münster et al. [7], Ahamed et al. [8] and Martinez-Sanchez et al. [9], who consider economic and environmental ramifications of food waste management.

Nevertheless, as the scope of this research area expands, systematic analyses are needed to obtain comparable results. Examples of frameworks with this aim have been developed for solid waste management (e.g. [10, 11]), but are less common for food waste management. A recent example of this is the framework recently developed by Manfredi et al. [12], which provides a useful six-step methodology to evaluate environmental and economic sustainability of different alternatives to manage food waste, with the aim of also incorporating social considerations.

The waste hierarchy applied to food products is a useful tool to rank waste management alternatives by sustainability performance. The waste hierarchy concept was introduced for the first time into European waste policy in 1975 [13], and has been continuously used until today in European Directives which have been implemented since then. It is also used in the UK by the Government and institutions such as Defra [14] and WRAP [15], and has been implemented in UK law [16]. There is a considerable number of research papers published in prestigious scientific journals discussing the waste hierarchy, plenty of them focussed on food waste, e.g. [17, 18]. More detailed information on the technologies described in the food waste hierarchy and their associated emissions can be found in the Best Available Techniques for the Waste Treatments Industries [19].

This paper describes a novel, systematic methodology to support sustainable decisions regarding management of food waste. With this objective, a nine-stage categorization and a version of the food waste hierarchy are used as a basis of a methodical procedure to identify types of food waste and alternative activities to manage them. As a result, a novel Food Waste Management Decision Tree is developed and discussed, and its applicability is tested using two case studies from the UK food manufacturing sector.

Methodology

Research Aim and Structure

The decision as to which is the most beneficial waste management alternative to utilise to manage food waste is usually made considering fundamentally only economic reasons and availability of waste management facilities. Furthermore, legislation delimits the range of solutions applicable to manage different types of food waste and therefore the decision is often made considering only a few alternatives. This paper seeks to add environmental and social considerations to the decision-making process so that more sustainable solutions can be achieved from the range of feasible waste management options. With this aim, the structure of the research presented in this paper is as follows: firstly, the definition of food waste used throughout this paper is provided; secondly, previous categorizations of food waste are discussed; thirdly, a categorization process is described based on the most pertinent indicators to classify food wastes; fourthly, the different types of food waste identified are linked to their most appropriate waste management alternatives, building a Food Waste Management Decision Tree; and finally, the categorization process is illustrated with two case studies from the UK food industry. A visual model of the research approach used can be seen in Fig. 1.

Definition of Food Waste

The first aspect to look upon in order to improve food waste management is to define unambiguously the exact meaning of 'food waste'. Unfortunately an agreement has not been reached yet and rather there are a range of definitions used. For consistency in this paper, food waste will be defined as food materials (including drinks) originally intended to be used to feed humans and not ultimately sold for human consumption by the food business under study, and inedible parts of food. Consequently, food sent to charities by companies is considered food waste in this paper, as it implies an economic loss to the food business, although from a biological and legal aspect this product remains being food and could be classified as

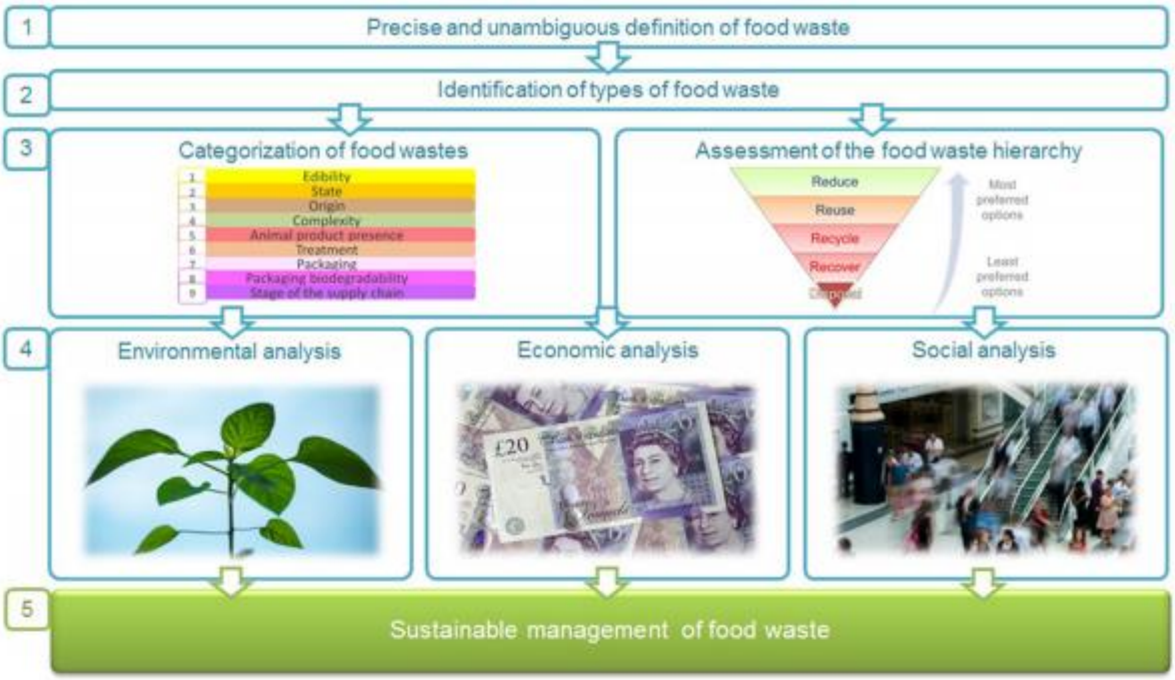


Fig. 1 Structure of the research presented in this paper

surplus food. Inedible parts of food are also included in the definition because waste is often composed of both edible and inedible parts difficult to separate, and food businesses must manage this waste. Inedible food waste is thus considered unavoidable waste. Any food used in other way than for human consumption is also considered food waste (e.g. animal feeding, industrial uses). On the other hand, food wasted by consumers and managed at home (e.g. home composting) falls out of the scope of this paper. Clearly, the inclusion of these factors in the definition is debatable; this paper studies the management of these materials and therefore they have been included in the term 'food waste'.

Review on Methods to Classify Food Waste

Categorization is a key step in order to identify the most appropriate waste management alternative for different types of food waste. Such categorization should consider all the divisions necessary to link different types of food waste with treatment methodologies in a way that their economic and social benefit are maximised and their environmental impact is minimized. Usually different studies use their own categorizations [20]. This section describes different attempts to classify food waste. These classifications are assessed and their usefulness to select optimal food waste management alternatives is discussed.

The most obvious categorization divides different types of food waste according to the type of food: cereals, fruits, meat, fish, drinks, etc. This categorization is useful to quantify the amount of food wasted based on mass (more commonly), energy content, economic cost, etc. There exist plenty of examples to classify food waste according to its food sector, e.g. [21, 22]. This type of classification is typically based on codes, e.g. the recently published Food Loss and Waste Accounting and Reporting Standard recommends the use of the Codex Alimentarius General Standard for Food Additives (GSFA) system or the United Nations' Central Product Classification (CPC) system as main codes, and when more precise classifications are needed, the Global Product Category (GPC) code or the United Nations Standard Products and Services Code (UNSPSC) as additional codes [23]. Additionally, food waste can be categorized with regard to its nutrient composition (e.g. carbohydrate and fat content [24]), chemical composition (e.g. C, H, N, O, S and Cl content [25]) or storage temperature (e.g. ambient, chilled or frozen [26]). Nonetheless, the information provided with these examples is not enough to prioritise some waste management alternatives against others.

In the UK, WRAP also identified the stages of the supply chain where food waste was generated (e.g. manufacturer, retailer) and assess the edibility of the waste. In this way, food waste can be avoidable (parts of the food that were actually edible), unavoidable (inedible parts of the food, such as bones, fruit skin, etc.) and possibly avoidable (food that some people would have eaten and others do not, such as bread crusts and potato skins) [27]. Different authors have further classified food waste at the household level as cooked/uncooked, as unpackaged/packaged food waste (when waste is packaged, it is additionally sorted as opened/unopened packaging) and according to their reason to disposal [28–30]. Other researchers also identified the leftovers and untouched food which goes to waste (e.g. [31]). Considering these options will be useful for a more comprehensive categorization, but there is still a lack of sections that further classify the waste in a way that a selection of the most appropriate waste management practice is facilitated. Furthermore, some of these classifications have been applied only to household food waste: a comprehensive categorization must include all stages of the food supply chain.

A more detailed attempt to classify food waste was carried out by Lin et al. [32], where food waste falls into the following categories: organic crop residue (including fruits and vegetables), catering waste, animal by-products, packaging, mixed food waste and domestic waste. In this study the potential for valorisation and some of the most appropriate options to manage the waste were assessed for each type of waste. However, the edibility of the waste and whether the food was fully processed during manufacturing were not considered.

Edjabou et al. [33] included two new factors: vegetable/animal-derived food waste and avoidable-processed/avoidable-unprocessed food waste. A more explicit classification with sub-categories was also suggested by Lebersorger and Schneider [20]. However the new sub-categories introduced, namely life cycle stage and packaging, are applicable only at the retail and household levels. They are irrelevant to improve the management of waste at other stages of the supply chain. On the other hand, Chabada et al. [34] used the 'seven wastes' approach from lean theory (namely transport, inventory, motion, waiting, overproduction, over-processing and defects) to classify categories of waste in fresh foods and identify the causes of waste generation, but not solutions for waste management. Garcia-Garcia et al. [35] suggested a number of indicators to classify food waste that provides useful information to delimit the range of waste management solutions applicable, nevertheless these indicators have not been used yet to identify the different types of food waste and propose the most appropriate waste management alternatives to manage them.

Therefore, a comprehensive and exhaustive analysis of all types of food waste has yet to be published. A holistic approach, where all relevant sub-categories of food wastes are identified and assessed, is necessary to support effective waste management. A solution to fill this knowledge gap is described in the following sections of this paper.

Indicators to Classify Food Waste

The previous section of the paper highlights the lack of a standardised and holistic approach to food waste management and the need for a classification process applicable to all types of food wastes as defined previously. The final aim of such a classification is to provide support for a better selection of alternatives to manage food waste. Any scheme should allow prioritisation of sustainability decisions in terms of the three pillars of sustainability:

(a) Economic ramifications, which can be either positive (economic benefit obtained from management of the waste) or negative (economic cost to dispose of the waste).
(b) Environmental impacts, which are usually negative (e.g. greenhouse gas emissions), but can also be positive (e.g. use of waste for the removal of pollutants in wastewater).
(c) Social considerations, which can be either positive (e.g. food redistributed to people in need) or negative (e.g. increased taxes).

The categorization proposed in this paper is based on nine indicators as explained by Garcia-Garcia et al. [35] and shown in Fig. 2. The assessment of these characteristics provides a systematic classification of the different types of food waste that enables a more appropriate selection amongst the available waste management alternatives. In each stage of the categorization process, one characteristic out of two or three options must be selected. Clarification of the different indicators can be found below:

1. *Edibility*: the product is edible if it is or has been expected to be consumed by humans at any point during its life cycle, otherwise the product is inedible. Inedible products include fruit skins, meat bones, some vegetable stalks, etc. When the product is edible from a biological point of view, but there is no demand for it (e.g. some types of offal, spent grain from breweries) it is considered inedible in this scheme, as it is not possible to reallocate it for human consumption. Therefore, the edibility of some food wastes can vary over time and geographical area considered. Various foods contain inedible parts when they are sold (e.g. banana and its skin); these food products are considered edible.
2. *State*: this characteristic must be assessed only for edible products. The product is eatable if it has not lost

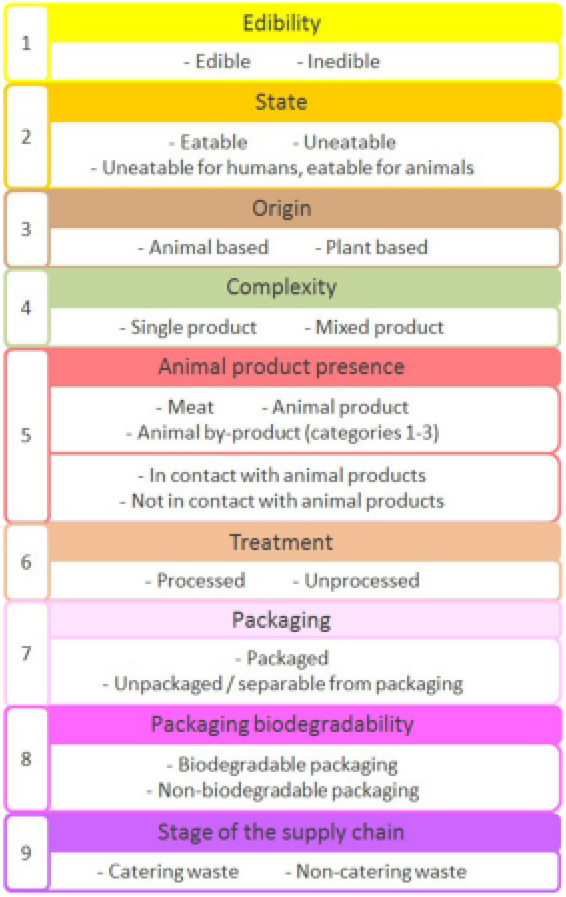


Fig. 2 Indicators to categorize food waste. Adapted from Garcia-Garcia et al. [35]

the required properties to be sold and fit for human consumption at the moment of its management as waste, otherwise the product is uneatable. If the food had not lost those properties, but requires further processing in the factory before being sold or consumed, it is classified as eatable and unprocessed (see indicator 6). A food product can become uneatable by being damaged at different points of the supply chain (e.g. overcooked during its manufacture, spilled during its distribution), being spoiled (e.g. leaving the cold chain), passing its use-by date, etc. If a product contains both uneatable and eatable parts and it is going to be managed as a whole, it must be considered uneatable. When the product is eatable from a biological point of view, there may still be ethical issues that can lead to classify it as uneatable to restrict its usage for human consumption, for instance to prevent using surplus alcoholic drinks for redistribution to charities, or products of lower quality to an acceptable established level. A third category includes products uneatable for humans because of safety concerns, but still fit for animal feeding (e.g. fallen from conveyor belts during manufacturing).

3. *Origin*: the product is animal based if it was produced by an animal (e.g. dairy products, eggs, honey) or using parts of animals (meat, including fish), otherwise the product is plant based. When the product contains both plant and animal-based materials (e.g. ready meals), it must be classified according to its predominant ingredient. If this is a plant ingredient the product will be also classified as a mixed product (see next categorization stage).
4. *Complexity*: this characteristic is only required for plant-based products. The product is single if it is formed of only one type of ingredient and it has not been in contact with other food material, otherwise the product is mixed.
5. *Animal product presence*: when the product is animal based, it must be categorized as meat (including fish), animal product (a product produced by animals) or by-product from animal bodies not intended for human consumption (e.g. by-products from slaughterhouses). In the last case, the waste should be further classified according to European regulations into Category 1, 2 or 3 [36]. When the product is plant based and mixed, it must be assessed as to whether the product contains any animal-based material or has been in contact with animal-based material.
6. *Treatment*: a food is considered processed when it has the same properties as the final product to be sold to the consumer (i.e. it has completed the manufacturing process, e.g. a ready meal; or the food does not need any processing before being distributed, e.g. fresh fruits and vegetables). If the food still needed any treatment at the moment of its management as waste it is unprocessed. Consequently, only edible and eatable waste should be assessed in this stage.
7. *Packaging*: a product is unpackaged if it is not contained in any packaging material. If the product is packaged but there is an available technology for unpacking and separating the food waste from its packaging, the product can be considered unpackaged; otherwise the product is packaged.
8. *Packaging biodegradability*: this characteristic must be assessed for packaged foods. Commonly, biodegradability of a material means that it can be digested by microorganisms, although the process may last for several months or years. Therefore, in this paper biodegradable packaging refers to that made of materials which have been tested and received a certificate of being "suitable for anaerobic digestion" or "compostable" in a technical composting plant (e.g. 'DIN

CERTCO' logo and the 'OK compost' logo). Biodegradable packaging is generally composed of paper, bioplastics, wood or any plant-based product. Typically non-biodegradable packaging is made of plastic, glass or metal.

9. *Stage of the supply chain*: catering waste includes domestic waste and waste from food services (e.g. restaurants, schools, hospitals, etc.); non-catering waste is generated in earlier stages of the supply chain (i.e. during farming, manufacturing, distribution or retailing).

The assessment of these nine stages, and the consequent determination of nine characteristics, is the starting point to select the most convenient waste management alternative. The hypothesis of this work is that each combination of nine indicators has associated with it one most favourable solution. The nine-stage categorization scheme is intended to be easy to apply and determinative for selection of the optimal waste management alternatives, taking into account regulations and economic, environmental and social ramifications. The next chapter proposes a set of waste management alternatives for the different food waste types identified following the categorization based on the nine indicators explained in this section.

Development and Partial Results

Having identified and classified the different food wastes following the guidelines presented in the previous section, the next step is to identify and analyse the food waste management alternatives. In order to do so, the waste hierarchy applied to food products is an appropriate tool to classify the different options to manage food waste, based on the sustainability of its results. The particular order of the different options in the hierarchy (i.e. the preference of some alternatives against others) is debatable (e.g. anaerobic digestion is considered better than composting), but the final aim is to prioritize options with better environmental, economic and social outcomes. Hence, there are several slightly different adaptations of the food waste hierarchy, however the most recent versions are usually based on the Waste Framework Directive 2008/98/EC [37]. An example of a food waste hierarchy which aims to prioritise sustainable management alternatives can be seen in Fig. 3; it is based on previous versions, including those of Defra et al. [14], Adenso-Diaz and Mena [38], Papargyropoulou et al. [17] and Eriksson et al. [18].

It is difficult to apply a waste hierarchy to food products due to the heterogeneity of these materials and the numbers of actors at different stages of the food supply chain that waste food. Therefore, the waste hierarchy must be assessed for each type of food waste, rather than for 'food waste' as a whole. This case-specific application of the waste hierarchy has been also recommended by Rossi et al. in their analysis of the applicability of the waste hierarchy for dry biodegradable packaging [39].

In this paper, environmental, economic and social ramifications associated with food waste management are considered, but impacts of the food during its life cycle are not included as they do not affect food waste management decisions (i.e. the impacts have already occurred before the food was wasted). Consequently, a life-cycle approach was not necessary to assess different alternatives and only end-of-life impacts were studied.

In order to link the categorization process and the waste management alternatives from the food waste hierarchy, the indicators described previously have been firstly used to identify the different types of food waste. Each indicator has been assessed and the superfluous categories for each indicator have been eliminated to simplify the analysis (e.g. state for inedible waste). The optimal waste management alternatives have been identified for each type of food waste in compliance with UK and European regulations and based on the food waste hierarchy, therefore prioritising the most sustainable solutions (Fig. 3). The result of this analysis has been represented in a diagram (namely Food Waste Management Decision Tree, FWMDT) that helps with analysing food waste using the indicators described. This FWMDT has been divided into four parts for display purposes and can be seen in Fig. 4 (edible, eatable animal-based food waste), Fig. 5 (edible, eatable, plant-based food waste), Fig. 6 (edible, uneatable food waste) and Fig. 7 (inedible and uneatable for humans, eatable for animals food waste).

The FWMDT functions as a flowchart. The user begins at the highest level, and selects the indicator that best describes the food waste (e.g. edible or inedible). The user then moves through subsequent levels of the diagram, following the arrows and making further indicator selections. At the bottom the user is presented with a set of waste management alternatives that differ according to the set of indicators for that food type.

The food waste must be broken down for analysis into the same subgroups as for the treatments to be applied, e.g. if a food business generates both plant-based waste and animal-based waste which are collected and treated separately, they must be also assessed independently. However, if a producer of convenience foods produces undifferentiated waste composed of both plant and animal products, this must be studied as a whole. In the latter example, the waste is classified as a mixed product. It is readily seen that separate collection provides the benefit that more targeted management practices can be carried out on the different food waste streams. When separate collection is not possible, a thorough waste sorting is still recommended,

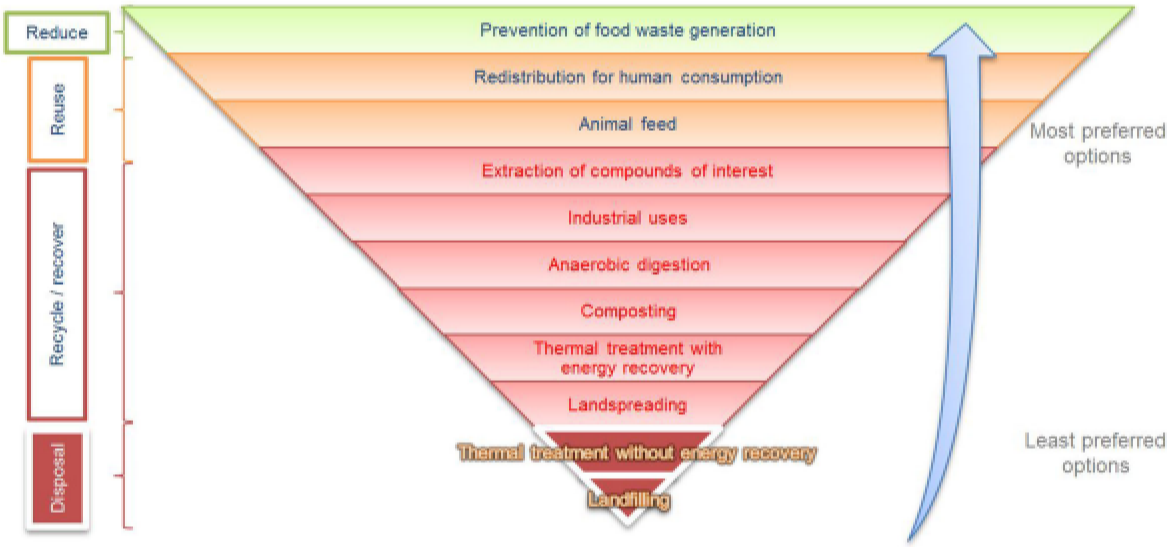


Fig. 3 Waste hierarchy for surplus food and food waste. Adapted from Garcia-Garcia et al. [35] and based on Defra et al. [14], Adenso-Diaz and Mena [38], Papargyropoulou et al. [17] and Eriksson et al. [18]

although some of the alternatives will not be available then (e.g. plant-based food waste that has been in contact with meat cannot be used for animal feeding).

The development of a categorization that covers all types of food waste is arduous due to the number of waste types and their dissimilarity. Similarly, there are numerous alternatives for food waste management. In Fig. 3 some of these numerous alternatives have been grouped—for instance, all processes for extracting substances from all types of food waste are included in extraction of compounds of interest. This is because there are dozens of chemical and physical routes to obtain bio-compounds from food products, and also numerous possibilities to use different types of food waste for industrial applications such as removal of pollutants from wastewater. It is therefore unfeasible to consider all these options explicitly for all the food waste categories. Consequently, in all cases when there are management alternatives other than redistribution and animal feeding suggested in the FWMDT, a targeted study for each type of waste must be carried out in order to find what opportunities there are to extract compounds of interest or for industrial use, before considering options lower down in the food waste hierarchy.

Additionally, prevention of food waste generation is not included in the FWMDT because is out of the scope of this research, and also this option would be always prioritised, as it is at the top of the food waste hierarchy and can potentially be applied to all types of edible food wastes. The option of prevention also includes alternative uses of products for human consumption (e.g. a misshapen vegetable that can be used in convenience foods). In these cases the products must be reprocessed and they would not be considered food waste according to the definition provided in the previous section, and therefore they are out of the scope of this work. If instead they are directly consumed without further processing the alternative to follow will be redistribution, although this will normally give a smaller economic benefit to the food company than selling them at their normal price. In this paper it is assumed that all prevention steps have been taken to minimize food waste generation, but nevertheless food waste is created and requires waste management optimisation.

Landspreading can be used with the majority of food waste types, but according to the food waste hierarchy (Fig. 3) this alternative is less beneficial than composting. As both alternatives can be used to treat the same types of food wastes, landspreading has not been further considered in this work and only composting has been examined.

Additionally, the last two waste management practices, namely landfilling and thermal treatment without energy recovery, are not considered in the analysis. Landfilling has a high environmental impact, and its economic and social outcomes are also negative. Treatment without energy recovery damages the environment likewise, but its economic and social ramifications are generally less adverse. In both cases there are always more sustainable management practices that can be used to manage food waste, even if these two alternatives could be potentially used with all types of food waste, regardless of their nature.

The FWMDT was designed as far as possible to embody the categories and indicators described in the previous section, but this was not always achievable. For instance,

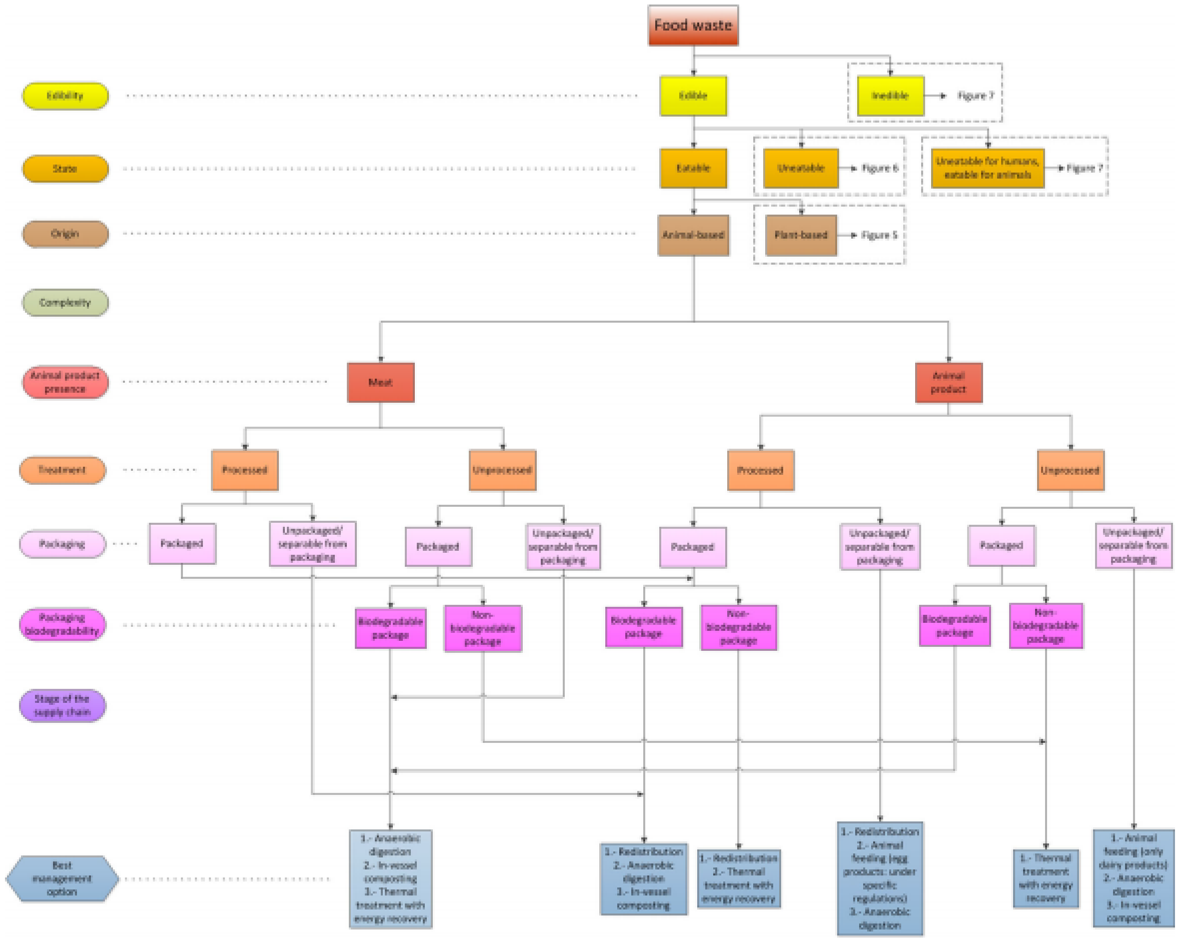


Fig. 4 Food Waste Management Decision Tree (FWMDT). Edible, eatable, animal-based food wastes and their most convenient waste management alternatives

the category animal-product presence includes additional indicators for inedible, animal-based products, as can be seen in Fig. 7, to comply with European regulations [36].

A description of each management alternative evaluated and the associated types of waste can be found below.

Redistribution for Human Consumption

Redistribution for human consumption is the optimal alternative, as food is used to feed people. Agreements with charities and food banks help to distribute surplus food to those in need. Products must be edible, eatable and processed, as defined in the previous section. It must be noted that processed does not necessarily mean that the final product was fully processed as initially planned by the food business, e.g. surplus potatoes for the preparation of chips for ready meals can be redistributed if they are fit for human consumption and distribution (for example, they have not been peeled yet) and comply with regulations. In this case the potatoes are defined as processed because they are as sold to final consumers. The European legislation redistribution for human consumption must meet is the General Food Law [40], the Food Hygiene Package [41–44], the Regulation (EU) No 1169/2011 [45], and the Tax legislation [46], as explained by O'Connor et al. [47]. An extensive study of the situation of food banks and food donation in the UK was carried out by Downing et al. [48].

Animal Feeding

This is the best alternative for foods which are not fit for human consumption but are suitable for animal feeding. In this category only farmed animals are considered (e.g. cattle, swine, sheep, poultry and fish). Pets, non-ruminant zoo animals, etc. are excluded, following guidelines explained in [49]. In order to be used for animal feeding,

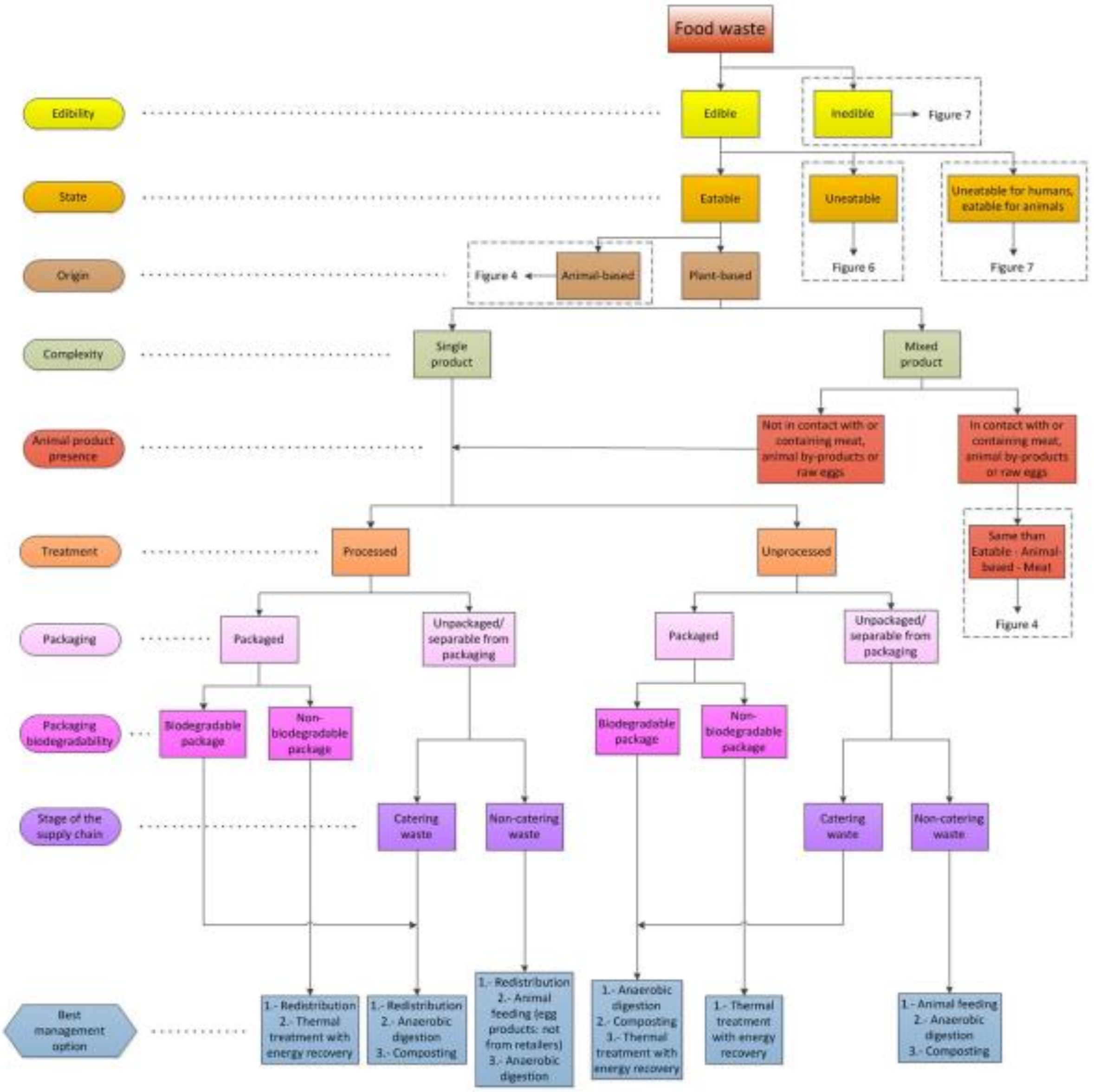


Fig. 5 Food Waste Management Decision Tree (FWMDT). Edible, eatable, plant-based food wastes and their most convenient waste management alternatives

products must either be eatable or uneatable for humans but eatable for animals, unpackaged or separable from packaging, and non-catering waste. Inedible, plant based, single product, non-catering waste can be used for animal feeding depending on the type of waste. This particular case must be assessed for each type of waste independently. When the product is mixed, it must be either not in contact with or containing meat, by-products from animal bodies or raw eggs if it is eatable, or not in contact with or containing animal-based products if it is inedible or uneatable for humans but eatable for animals. Mixed waste containing animal products from manufacturers is suitable for animal feeding when the animal product is not the main ingredient. Meat (or plant-based products containing meat) cannot be sent for animal feeding. Eggs and egg products (or plant-based products containing them) must come from the agricultural or manufacturing stage when used for animal feeding and must follow specific treatments. Milk and dairy products can be used for animal feeding if they are processed (the processing needed is similar to that for human

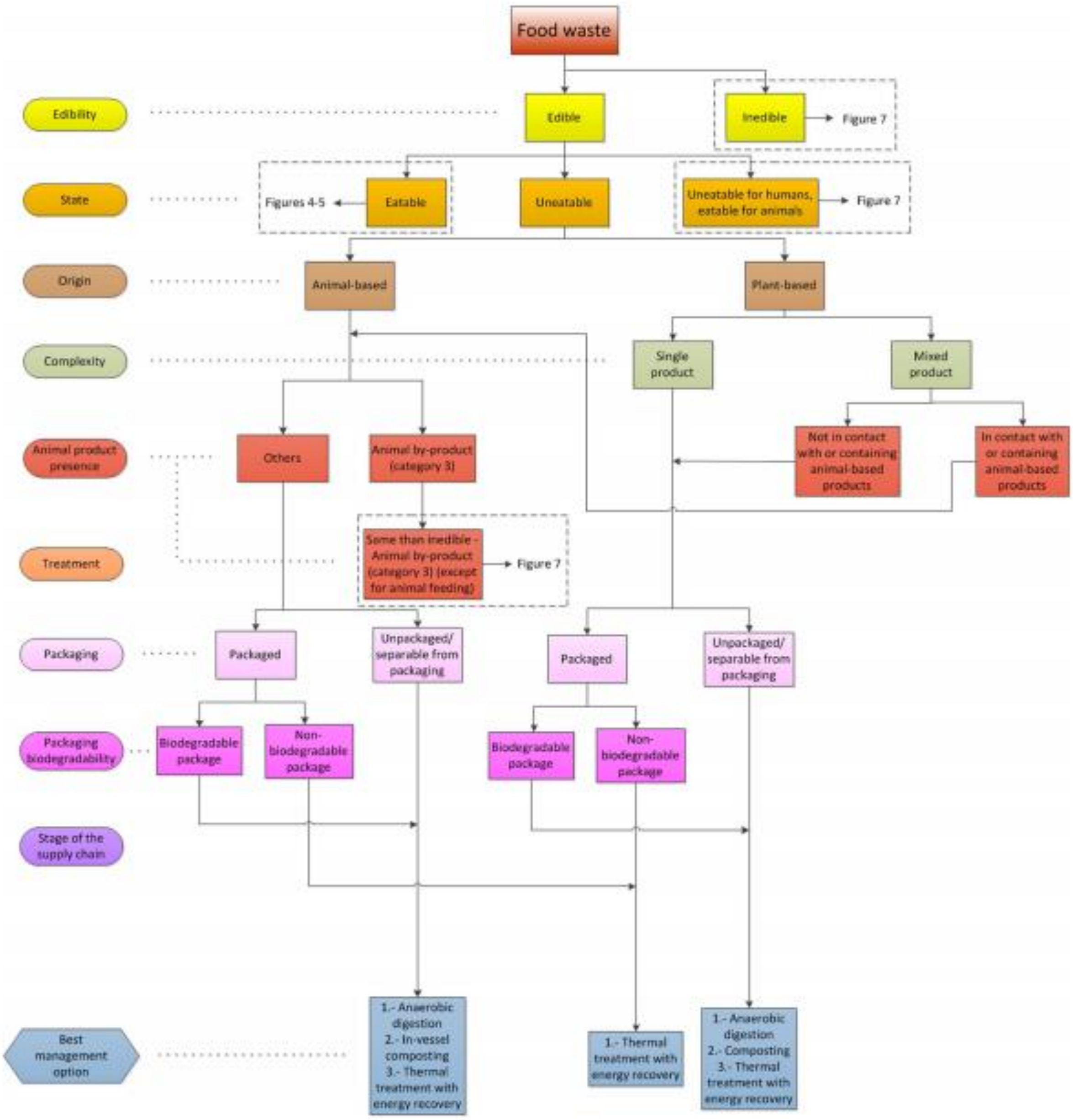


Fig. 6 Food Waste Management Decision Tree (FWMDT). Edible, uneatable food wastes and their most convenient waste management alternatives

consumption), or unprocessed under UK rules if the farm is a registered milk processing establishment. Inedible, animal based, category 3 waste can also be used for animal feeding only under the conditions listed in the FWMDT (Fig. 7). According to European regulations, all types of category 3 animal by-products can be used in animal feed except hides, skins, hooves, feathers, wool, horns, hair, fur, adipose tissue and catering waste. Nevertheless the UK regulation is stricter than European regulations and this has been incorporated into the FWMDT. It must be noted that technically some category 3 animal by-products are edible, but they are not intended for human consumption. In any case, they must be not spoiled in order to be usable for animal feeding, and in most cases they must be processed following specific requirements before being used. If a waste contains different categories of animal by-products,

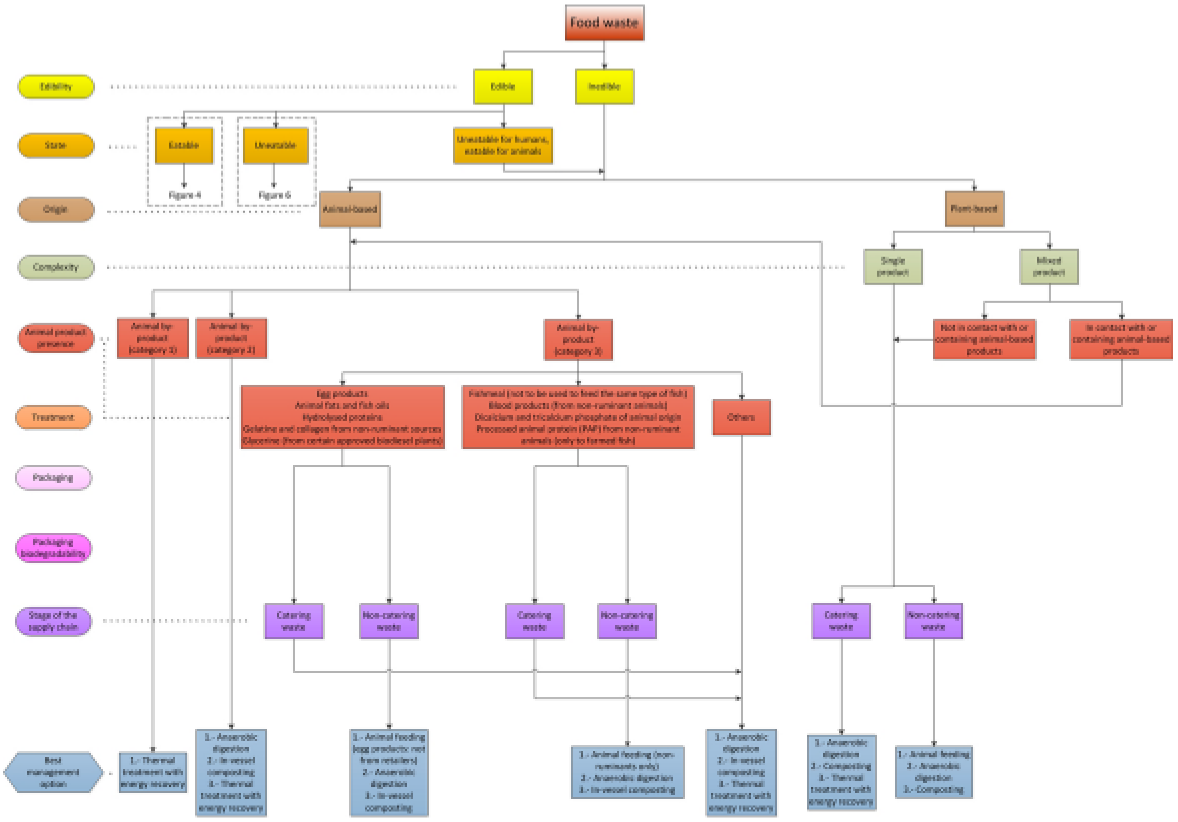


Fig. 7 Food Waste Management Decision Tree (FWMDT). Inedible and uneatable for humans, eatable for animals food wastes and their most convenient waste management alternatives. The list of materials classified as animal by-products categories 1–3 can be found in [36]

it must be treated following the requirements of the material with the highest risk (category 1: highest risk, category 3: lowest risk). The following sources have been used to develop the FWMDT and must be consulted when using animal by-products in animal feeds: European regulations [36, 50, 51] and UK legislation [52]. Useful guidance information on this matter in the UK can be found at [49, 53]. Further information on additional legislation that applies to work with animal by-products can be found at [54] and [55] for milk products. Eggs must be treated in a processing facility under national rules [56]. The following additional legislation for animal feeding has also been consulted: European regulations [57–59] and regulations in England [60]. General guidance on animal feeding was collected by Food Standards Agency [61].

Anaerobic Digestion

Anaerobic digestion can be used with all types of food waste except animal by-products category 1 and packaged waste (i.e. non-separable from packaging) in a non-biodegradable packaging. The animal by-products category 3 must be pasteurised; the particle size of animal by-products category 2 must be 50 mm or smaller, and its core must have reached a temperature of 133 °C for at least 20 min without interruption at an absolute pressure of at least 3 bar [36, 52, 62]. Anaerobic digestion plants in the UK must comply with regulations with regard to environmental protection, animal by-products, duty of care, health and safety and waste handling (more information about the different legal requirements can be found in [63]).

Composting

The types of material suitable for composting are the same as for anaerobic digestion: all food waste except animal by-products category 1 and packaged waste (i.e. non-separable from packaging) in non-biodegradable packaging. Animal by-products category 2 can be composted if processed according to regulations [36, 52]. Composting must be carried out in closed vessels (in-vessel composting) if the waste contains or has been in contact with any animal-based material [15, 62], as it can attract vermin. Further guidance for the composting of waste can be found in [64].

Thermal Treatment with Energy Recovery

This alternative can be applied to every type of food waste; nevertheless its use must be minimized as it provides small benefit compared to the impacts generated. Additionally, a great quantity of energy is needed to treat food waste due to its mainly high water content, and therefore this alternative may be useful and give an energy return on investment when treating dry food wastes (e.g. bread and pastries) or food waste mixed with other materials, such as in municipal solid waste. Thermal treatments with energy recovery, which includes incineration, pyrolysis and gasification, is the only alternative available to treat packaged food (non-separable from packaging) in non-biodegradable packaging, except the cases when the product is also edible, eatable and processed, and therefore can be redistributed for human consumption. As this type of waste is the final packaged product it will usually be generated in the last stages of the supply chain, particularly at retailing and consumer level (municipal solid waste). Thermal treatments with energy recovery are also the most appropriate alternative to treat animal by-products category 1, and in some cases, it is also necessary to process by pressure sterilisation [36, 52]. Useful information on incineration of municipal solid waste can be found in [65] and on technologies and emissions from waste incineration in the Best Available Techniques for Waste Incineration [66].

Final Results and Discussion: Case Studies

Introduction to Case Studies

The food waste categorization process presented in this paper has been applied to two case studies to demonstrate its applicability: a brewery (Molson Coors) and a manufacturer of meat-alternative products (Quorn Foods). These food companies were selected because previous contact between the researchers and the industries existed, and also due to their leading position in their product market, large size and therefore a predictable number of different types of food waste produced. A visit to their headquarters took place in June 2015, in which interviews were held with company employees. A questionnaire was used to systematically identify food waste streams and collect relevant data.

The categorization of these wastes according to the categorization scheme and the most favourable waste treatment alternatives identified using the FWMDT (Figs. 4–7) are explained in the following sections. The rest of the alternatives from the food waste hierarchy were also assessed for each type of food waste.

Brewery: Molson Coors

This section categorizes the different types of food waste generated at one of Molson Coors' manufacturing sites, a brewery situated in central England. The different types of food waste generated, in order of decreasing quantity, are: spent grain, waste beer, conditioning bottom, filter waste and trub. The quantity of waste generated during a year is only dependent on the level of production, since a relatively constant percentage of waste is generated per amount of final product manufactured. The different types of food waste identified are categorized in Table 1 and explained below.

Spent Grain

Spent grain accounts for around 85 % of the total food waste in the manufacturing plant. It is an unavoidable by-product of the mashing process and is formed of barley and small amounts of wheat.

According to the FWMDT (Fig. 7), the best option is to send the waste for animal feeding. Currently spent grain is mixed with trub (in an approximate proportion of 99 % spent grain, 1 % trub) and used for animal feeding. However, the possibility of reprocessing the waste to adapt it for human consumption was also assessed, as suggested in the previous subsection. Spent grains contain high proportions of dietary fibres and proteins which may provide a number of health benefits [67]. Spent grain should not be mixed with trub if it is intended to use it to produce food products. Flour can be produced from spent grain following a process that includes drying and grinding [67]. This can be mixed afterwards with wheat flour and used in a wide range of food products such as bread, muffins, biscuits, etc., increasing their health benefits [68]. It must be noted that production of new food products was not selected by using the FWMDT because spent grain was considered inedible, as there is no current consumer demand for the products described above. If technology existed to produce new food products from spent grain, such as those described above, and these products could be sold because there was a consumer demand for it, spent grain would not be considered food waste providing it was used for this purpose.

Other uses for spent grain, apart from food uses and for animal fodder, include pet food, use in construction bricks, removal of pollutants in wastewater, production of paper, growing medium for mushrooms or microorganisms, extraction and synthesis of compounds (e.g. bioethanol, lactic acid, polymers and resins, hydroxycinnamic acids, arabinooligoxylosides, xylitol, pullulan), anaerobic digestion, composting, thermal treatment with energy recovery and landspreading [68–70].

Table 1 Types of food waste in Molson Coors and their management alternatives

	Spent grain	Waste beer	Conditioning bottom	Filter waste	Trub
Edibility	Inedible	Edible	Edible	Inedible	Inedible
State	N/A	Eatable	Eatable	N/A	N/A
Origin	Plant based	Plant based	Principally microorganisms*	Microorganisms*	Plant based
Complexity	Single product	Single product	Single product	Mixed product	Mixed product
Animal-product presence	N/A	N/A	N/A	Not in contact with animal-based products	Not in contact with animal-based products
Treatment	N/A	Processed	Unprocessed	N/A	N/A
Packaging	N/A	Separable from packaging	Unpackaged	N/A	N/A
Packaging biodegradability	N/A	N/A	N/A	N/A	N/A
Stage of the supply chain	Non-catering waste	Non-catering waste	Non-catering waste	Non-catering waste	Non-catering waste
Current treatment	Animal feeding	95 % animal feeding + 5 % sewage	Animal feeding	50 % compost + 50 % sewage	Animal feeding
Suggested alternative	Animal feeding	Redistribution for human consumption	Animal feeding	Anaerobic digestion	Animal feeding
Further possibilities	Production of foodstuff	N/A	Production of foodstuff	Industrial uses	Production of foodstuff
Quantity	≈70,000 t/year	14,000 t/year	7000 t/year	1200 t/year	≈700 t/year

The suggested alternative is based on the FWMDT presented in the Figs. 4–7. Possible alternative options from the food waste hierarchy are suggested as further possibilities when they are better than the suggested alternative. The particular type of diatomaceous earth in filter waste was not identified and thus it was considered to be not suitable for animal feeding. N/A means 'not applicable' or that the information is not necessary. * The 'microorganisms' indicator, from the origin stage, was considered as plant based

Waste Beer

This waste corresponds to the final product which is not ultimately consumed. There are three reasons as to why this waste is generated:

(a) Beer left in casks brought back from the food service sector, which accounts for most of the waste in this category. It means an economic loss to the food service sector, not to the brewing company; therefore, it has not been given a high importance by the beer producer.
(b) Beer rejected because of mislabelling.
(c) Spilled beer in the filling process, which accounts for a negligible amount.

Currently, 95 % of the waste is sent to farms and mixed with other waste to feed animals (pigs). The remaining 5 % is sent to sewage.

Ideally, and according to the FWMDT (Fig. 5), beer left in casks could be reused for human consumption; however, as this comes from outside of the factory, it is difficult to prove that it has not been altered and is safe for consumption. If the option of redistribution for human consumption is discarded, the next recommended alternative is animal feeding, which is the current final use.

Beer rejected because of mislabelling is perfectly potable, so it is potentially reusable; however, there is difficulty of extracting the product from its packaging (i.e. emptying bottles and dispensing the product into new bottles). This would require significant employee time or new technologies for automation of the process, but would prevent beer from being wasted. Alternatively, in England the mislabelled beer can be sold at a lower price to a redistributor of surplus products such as Company Shop, where the label is corrected to meet Food Information Regulations 2014 [71], and providing the beer is compliant with food safety legislation it can be sold at a lower price to the final consumer. Similarly, European legislation that regulates the food information that must be provided to consumers in product labelling is the Regulation (EU) No 1169/2011 [45]. Food banks generally do not serve beer and therefore in these cases it cannot be redistributed to charities for people in need.

Alternatively, extraction of alcohol from waste beer by distillation could also give an economic benefit.

Conditioning Bottom

This waste is an unavoidable by-product which settles to the bottom of the conditioner tanks during the maturation process. It is composed principally of yeast, thus it is edible. However, it is not suitable for redistribution for human consumption, as the waste is not processed. Currently it is sent for animal feeding (pigs), which is the optimal alternative according to the FWMDT (Fig. 5).

Alternatively, some substances from the conditioning bottom can be used to produce new food products. Yeast can be separated and used to produce foodstuff. In order to recover yeast, the sediment should be filtered and squeezed, and this gives the opportunity to recover cloudy-type beer. As well as with spent grain, discussed previously, production of new food products was not selected by using the FWMDT because conditioning bottom is unprocessed, as there is either no current consumer demand for it or no technology available to undertake the processes required.

Filter Waste

Filter waste is formed of diatomaceous earth, yeasts and proteins. Yeast and proteins are edible; typically diatomaceous earth (i.e. fossilized remains of diatoms) is considered inedible; however there are two types: food grade diatomaceous earth and inedible diatomaceous earth. In order to choose the best waste management alternative the type of diatomaceous earth must first be identified. As the current use for beer production is as a filter medium, it will be assumed to be inedible diatomaceous earth.

Following the FWMDT (Fig. 7), the waste should be used in animal feeds. However, the type of diatomaceous earth used is not suitable for animal feeding and therefore the next alternative from the food waste hierarchy was suggested: anaerobic digestion to obtain energy. Currently, filter waste is sent to composting (when it is dry) and sewage (when it is wet). As composting is an alternative under anaerobic digestion in the waste hierarchy and sewage is at the bottom of the hierarchy, there is an important opportunity for improvement. Potential additional uses of diatomaceous earth include industrial (filter medium, stabiliser of nitroglycerin, abrasive in metal polishes and toothpaste, thermal insulator, reinforcing filler in plastics and rubber, anti-block in plastic films, support for catalysts, activation in blood coagulating studies, cat litter, etc.), additive in ceramic mass for the production of red bricks, insecticide and anticaking agent for grain storage (when it is food grade), growing medium in hydroponic gardens and plotted plants and landspreading [72, 73].

Trub

This is an unavoidable by-product obtained principally in the separator after the brewing process. It is formed of hops, inactive yeast, heavy fats and proteins. Currently this waste is mixed with spent grain and sent to animal feeding, which is the best alternative according to the FWMDT (Fig. 7).

On the other hand, while hops are typically considered inedible, some parts are actually edible. For example, hop shoots can be consumed by humans [74]. Ideally edible parts of the hops would be separated and used in food products and the remaining hops be sent to animal feeding. Yeast, fats and proteins could potentially be used in food products. As well as with spent grain, discussed previously, production of new food products was not selected by using the FWMDT because trub was considered inedible, as there is either no current consumer demand for the products described above or no technology available to undertake the processes required.

Applicability of the Categorization Process and the FWMDT

The FWMDT was proved to be useful to classify food waste generated at Molson Coors, as two types of waste were identified to be upgradeable: waste beer and filter waste could be managed in an alternative way in which more value would be obtained.

The assessment of some categories was complex for some food wastes, e.g. edibility for spent grain and waste beer. Spent grain was demonstrated to be edible, but as there is no market for this product for human consumption spent grain waste was consequently further classified as inedible. Research and investment to produce new food products from spent grain is encouraged, and when that takes place the categorization of spent grain will have to be amended. Waste beer was classified as eatable, however safety concerns regarding beer left in casks brought back from the food service sector must be overcome before the beer is reused. Should waste beer be considered safe for consumption but of low quality, ethical issues may arise regarding the benefits of using it for human consumption. Following the FWMDT, redistributing safe food for human consumption is always better from a sustainable point of view than any other alternative from the food waste hierarchy.

The feasibility to send food waste to animal feeding was also difficult to assess. It was found that when considering animal feeding for inedible, plant-based, single or mixed product not in contact with or containing animal-based products, non-catering waste (Fig. 7) each type of food waste should be analysed independently. For instance, trub can be sent for animal feeding but filter waste not because it contains diatomaceous earth which cannot be digested by animals.

Additionally, waste formed principally of yeast could not be strictly classified as plant-based or animal-based. The 'microorganisms' indicator was introduced for this reason, but in practice this was considered as plant-based material, since it is not under animal by-product regulations.

Molson Coors also generates a by-product from the mashing process, spent yeast, which is currently sold to a food company nearby to produce Marmite®, a food spread. Since this by-product is sold as planned by Molson Coors to produce a food product, it is not considered food waste according to the definition provided previously, and therefore is out of the scope of this work. If spent yeast were sent for any other use, it would be considered food waste and would have to be analysed using the FWMDT.

Manufacturer of Meat Alternatives: Quorn Foods

This section categorizes the different types of food waste generated at Quorn Foods, a manufacturer of meat alternatives situated in Northern England. Two types of food waste were identified: food solid/slurry mix and food product returns, which account for 63 and 21 % of the total waste in the factory respectively. The rest of the waste is non-food materials such as cardboard, plastic, etc. The quantity of waste generated during a year is only conditional on the level of production: a relatively constant percentage of waste is generated per amount of final product manufactured. The different food waste types are listed and categorized in Table 2 and explained below.

Food Solid/Slurry Mix

This category of waste includes products being lost through the production line: product falling from conveyor belts, trimmings, product stuck onto inner walls of the industrial equipment, etc. It has the same ingredients as the final product: fungus (mycoprotein), plant-based material, and animal-based products (egg albumen) in low proportions: 2–3 % by mass of the final product. It is an avoidable waste as it could be reduced or eliminated with more appropriate industrial equipment.

This waste was considered eatable, as it is generated only because of the inefficiency of the systems rather than to due to problems with the product. However, a more detailed analysis should be carried out to identify all different cases where this waste is generated and assess their state. If uneatable waste (e.g. spilled food onto the floor) is found, this should be classified as a different category of waste [75], although the new food waste management alternative for this waste according to the FWMDT would remain unchanged in this particular case: animal feeding.

Considering the previous comments, the most beneficial alternative according to the FWMDT (Fig. 5) is animal feeding, which is the option currently followed by the company. Unfortunately, this does not provide any economic income at present.

An investment in improvements in the industrial equipment would reduce the amount of food wasted in this category. Alternatively, the waste generated could be recovered and used to produce more final product.

Food Product Returns

Food product returns is the final product which cannot be sold to the final consumer for a number of reasons, including incorrect formulation, no traceability, packaging errors, etc. It has the same ingredients as the final product: fungus (mycoprotein), plant-based material, and animal-based products (egg albumen) in low proportions: 2–3 % by mass of the final product. It is an avoidable waste as it could be reduced or eliminated with more appropriate manufacturing practices.

This waste was considered eatable, as it corresponds to the final product. However, a more detailed analysis must be carried out before redistributing the food for human consumption in order to identify all different cases where this waste is generated and assess their state. If uneatable waste is found (e.g. its use-by date has passed), it must be classified as a different category of waste and this will allow a bespoke solution for this type of food waste. In this case, since the product is packaged, there is no risk of uneatable waste contaminating eatable waste.

Considering the previous comments, the most beneficial alternative is redistribution for human consumption, according to the FWMDT (Fig. 5). Currently the waste is separated from its packaging and sent to anaerobic digestion. The remaining packaging is used to produce refuse-derived fuel.

Applicability of the Categorization Process and the FWMDT

The FWMDT was proved to be useful to classify food waste generated at Quorn Foods, as one type of waste was identified to be upgradeable: food product returns could be managed in an alternative way in which more value would be obtained.

A more detailed analysis would be useful to identify sub-types of food waste and consequently the categorization process should be completed for all new food wastes found. This would provide a tailored waste management alternative for each type of food waste. For instance, if a

Table 2 Types of food waste in Quorn Foods and their management alternatives

	Food solid/slurry mix	Food product returns
Edibility	Edible	Edible
State	Eatable	Eatable
Origin	Fungus*	Fungus*
Complexity	Mixed product	Mixed product
Animal-product presence	Not in contact with or containing meat, animal by-products or raw eggs	Not in contact with or containing meat, animal by-products or raw eggs
Treatment	Unprocessed	Processed
Packaging	Unpackaged	Separable from packaging
Packaging biodegradability	N/A	N/A
Stage of the supply chain	Non-catering waste	Non-catering waste
Current treatment	Animal feeding	Anaerobic digestion
Suggested alternative	Animal feeding	Redistribution for human consumption
Further possibilities	Production of foodstuff	N/A
Quantity	1000 t/year	≈ 360 t/year

The suggested alternative is based on the FWMDT presented in the Figs. 4–7. Possible alternative options from the food waste hierarchy are suggested as further possibilities when they are better than the suggested alternative. N/A means 'not applicable' or that the information is not necessary. * The 'fungus' indicator, from the origin stage, was considered as plant based

final product for which the use-by date has passed is found, this could be named as 'expired food product returns' and its most appropriate waste management alternative would be anaerobic digestion, unlike the current generic 'food product returns' which should be redistributed.

Additionally, waste formed principally of fungus could not be strictly classified as plant-based or animal-based. The 'fungus' indicator was introduced for this reason, but in practice this was considered as plant-based material, since it is not covered by animal by-product regulations.

Conclusions

The food waste categorization and management selection flowchart (i.e. the Food Waste Management Decision Tree) discussed in this paper facilitates the selection of the most sustainable food waste management alternative, with the objective of minimizing environmental impacts and maximising economic and social benefits. The categorization is intended to be easy to apply, facilitating identification of the type of food waste generated, and its link with the most appropriate food waste management alternative. This methodology has been illustrated with case studies from two large UK food and drink manufacturers. Their food waste types have been identified and their existing waste management practices compared to the proposed alternatives. It was found that a detailed breakdown of the types of food waste provides significantly better results than general itemisation, since bespoke solutions can be used for each food waste.

The analysis described can be applied to every type of food waste from every stage of the food supply chain. However, this methodology is expected to be more useful in the early stages (agricultural and manufacturing) of the food supply chain, where separate collection is generally carried out more effectively, than in the retailing and consumer stages where waste is often sent to municipal solid waste. Additionally, it is recommended to adapt the categorization to each food sector or business and include more waste management alternatives in the analysis (e.g. extraction of compounds of interest from food waste).

Unfortunately, the alternatives at the top of the food waste hierarchy are applicable to fewer food waste types than those at the bottom. Consequently, a range of solutions is required for a tailored treatment of each food waste type. A clear example of this is the reduction in the previously widespread use of food waste for animal feeding. This is due to stricter regulation that has resulted in fewer types of food waste that can be used to feed animals [76]. Health and safety concerns influence legislation on food waste management, but excessively zealous bans of food waste management options results in the unintended consequence that less advantageous alternatives are more commonly used. Regarding the animal feeding example, there are initiatives to change legislation and allow more types of food waste to be fed to animals [77].

The food waste categorization scheme is also useful for monitoring purposes. It provides an easy way to classify food waste in a business or a region to assess progress in management and sustainability and measure against other companies or areas. In order to do that, firstly a clear definition of food waste must be agreed, the boundaries of the system to analyse must be delimited, and afterwards the food waste types can be identified and quantified.

Evaluating the relative merits of waste management alternatives is a complex task. The factors determining which solution is more convenient are difficult to assess and sometimes even difficult to identify, including yields of the processes, proximity of waste management facilities, tax regulations, and demand for by-products, amongst many others. As a consequence, the waste hierarchy should be applied to every type of food waste identified independently, rather than to food waste as a whole, and undertake an exhaustive analysis for each food waste. To meet this challenge the authors are developing an analysis method and associated figures of merit to allow quantitative comparison of waste management alternatives, with a focus on environmental impacts, as an improvement over the current, qualitative approach.

Acknowledgments This research is funded by the Engineering and Physical Sciences Research Council (EPSRC) UK through the Grant EP/K030957/1.

References

1. Food and Agriculture Organization of the United Nations (FAO): Global food losses and food waste—extent, causes and prevention, Rome (Italy) (2011)
2. Institute of Mechanical Engineers: Global Food—Waste Not. Want Not, London, UK (2013)
3. United Nations: Resolution adopted by the General Assembly on 25 September 2015. Transforming our world: the 2030 Agenda for Sustainable Development (2015)
4. Food and Agriculture Organization of the United Nations (FAO): Toolkit. Reducing the Food Wastage Footprint (2013)
5. Griffin, M., Sobal, J., Lyson, T.A.: An analysis of a community food waste stream. Agric. Human Values **26**, 67–81 (2009)
6. Thyberg, K.L., Tonjes, D.J.: A management framework for municipal solid waste systems and its application to food waste prevention. Systems **3**, 133–151 (2015)
7. Münster, M., Ravn, H., Hedegaard, K., Juul, N., Ljunggren Söderman, M.: Economic and environmental optimization of waste treatment. Waste Manag. **38**, 486–495 (2015)
8. Ahamed, A., Yin, K., Ng, B.J.H., Ren, F., Chang, V.W.-C., Wang, J.-Y.: Life cycle assessment of the present and proposed food waste management technologies from environmental and economic impact perspectives. J. Clean. Prod. **131**, 607–614 (2016)
9. Martinez-Sanchez, V., Tonini, D., Møller, F., Astrup, T.F.: Life-cycle costing of food waste management in Denmark: importance of indirect effects. Environ. Sci. Technol. **50**, 4513–4523 (2016)
10. Harrison, K.W., Dumas, R.D., Solano, E., Barlaz, M.A., Downey Brill, E.J., Ranjithan, S.R.: Decision support tool for life-cycle-based solid waste management. J. Comput. Civ. Eng. **15**, 44–58 (2001)
11. Karmperis, A.C., Aravossis, K., Tatsiopoulos, I.P., Sotirchos, A.: Decision support models for solid waste management: review and game-theoretic approaches. Waste Manag. **33**, 1290–1301 (2013)
12. Manfredi, S., Cristobal, J.: Towards more sustainable management of European food waste: methodological approach and numerical application. Waste Manag. Res. 0734242X16652965 (2016)
13. The Council of the European Communities: Council Directive of 15 December 1975 on waste (75/442/EEC). Off. J. Eur. Communities. L 194/39–41 (1975)
14. Defra, Environment Agency, WRAP: Applying the Waste Hierarchy: evidence summary. London (UK) (2011)
15. Waste & Resources Action Programme (WRAP): Applying the waste hierarchy: a guide to business (2011)
16. Statutory Instruments: The Waste (England and Wales) Regulations 2011 (2011)
17. Papargyropoulou, E., Lozano, R., Steinberger, J.K., Wright, N., bin Ujang, Z.: The food waste hierarchy as a framework for the management of food surplus and food waste. J. Clean. Prod. **76**, 106–115 (2014)
18. Eriksson, M., Strid, I., Hansson, P.-A.: Carbon footprint of food waste management options in the waste hierarchy—a Swedish case study. J. Clean. Prod. **93**, 115–125 (2015)
19. European Commission: Reference document on Best Available Techniques for the Waste Treatments Industries (2006)
20. Lebersorger, S., Schneider, F.: Discussion on the methodology for determining food waste in household waste composition studies. Waste Manag. **31**, 1924–1933 (2011)
21. Flores, R.A., Shanklin, C.W., Loza-Garay, M., Wie, S.H.: Quantification and characterization of food processing wastes/residues. Compost Sci. Util. **7**, 63–71 (1999)
22. Malamis, D., Moustakas, K., Bourka, A., Valta, K., Papadaskalopoulou, C., Panaretou, V., Skiadi, O., Sotiropoulos, A.: Compositional analysis of biowaste from study sites in Greek municipalities. Waste Biomass Valoriz. **6**, 637–646 (2015)
23. Food Loss + Waste Protocol: Food Loss and Waste Accounting and Reporting Standard (2016)
24. Russ, W., Meyer-Pittroff, R.: Utilizing waste products from the food production and processing industries. Crit. Rev. Food Sci. Nutr. **44**, 57–62 (2004)
25. Hla, S.S., Roberts, D.: Characterisation of chemical composition and energy content of green waste and municipal solid waste from Greater Brisbane, Australia. Waste Manag. **41**, 12–19 (2015)
26. Mena, C., Adenso-Diaz, B., Yurt, O.: The causes of food waste in the supplier-retailer interface: evidences from the UK and Spain. Resour. Conserv. Recycl. **55**, 648–658 (2011)
27. Bridgwater, E., Quested, T.: Waste & Resources Action Programme (WRAP). Synthesis of Food Waste Compositional Data 2012 (2013)
28. Ventour, L.: Waste & Resources Action Programme (WRAP). The food we waste (2008)
29. Quested, T., Murphy, L.: Waste & Resources Action Programme (WRAP). Household food and drink waste: A product focus (2014)
30. Schott, A.B.S., Andersson, T.: Food waste minimization from a life-cycle perspective. J. Environ. Manage. **147**, 219–226 (2015)
31. Matsuda, T., Yano, J., Hirai, Y., Sakai, S.: Life-cycle greenhouse gas inventory analysis of household waste management and food waste reduction activities in Kyoto, Japan. Int. J. Life Cycle Assess. **17**, 743–752 (2012)

32. Lin, C., Pfaltzgraff, L.A., Herrero-Davila, L., Mubofu, E.B., Solhy, A., Clark, P.J., Koutinas, A., Kopsahelis, N., Stamatelatou, K., Dickson, F., Thankappan, S., Zahouily, M., Brocklesby, R., Luque, R.: Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. Energy Environ. Sci. **6**, 426–464 (2013)
33. Edjabou, M.E., Jensen, M.B., Götze, R., Pivnenko, K., Petersen, C., Scheutz, C., Astrup, T.F.: Municipal solid waste composition: sampling methodology, statistical analyses, and case study evaluation. Waste Manag. **36**, 12–23 (2015)
34. Chabada, L., Dreyer, H.C., Romsdal, A., Powell, D.J.: Sustainable Food Supply Chains: Towards a Framework for Waste Identification. In: Emmanouilidis, C., Taisch, M., Kiritsis, D. (eds.) Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services, pp. 208–215. Springer, Berlin (2013)
35. Garcia-Garcia, G., Woolley, E., Rahimifard, S.: A framework for a more efficient approach to food waste management. Int. J. Food Eng. **1**, 65–72 (2015)
36. The European Parliament and the Council of the European Union: Regulation (EC) No 1069/2009 of the European Parliament and of the Council of 21 October 2009. Off. J. Eur. Union. L 300/1–33 (2009)
37. The European Parliament and the Council of the European Union: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008. Off. J. Eur. Union. L 312/3–30 (2008)
38. Adenso-Diaz, B., Mena, C.: Food industry waste management. In: Tiwari, B.K., Norton, T., Holden, N.M. (eds.) Sustainable Food Processing, pp. 453–462. Wiley-Blackwell, Chichester (2014)
39. Rossi, V., Cleeve-Edwards, N., Lundquist, L., Schenker, U., Dubois, C., Humbert, S., Jolliet, O.: Life cycle assessment of end-of-life options for two biodegradable packaging materials: sound application of the European waste hierarchy. J. Clean. Prod. **86**, 132–145 (2015)
40. The European Parliament and the Council of the European Union: Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 (2002)
41. The European Parliament and the Council of the European Union: Corrigendum to Regulation (EC) No 852/2004 of the European Parliament and of the Council of 29 April 2004 on the hygiene of foodstuffs. Off. J. Eur. Union. L 226/3–21 (2004)
42. The European Parliament and the Council of the European Union: Corrigendum to Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for food of animal origin. Off. J. Eur. Union. L 226/22–82 (2004)
43. The European Parliament and the Council of the European Union: Corrigendum to Regulation (EC) No 854/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific rules for the organisation of official controls on products of animal origin intended for human consumption. Off. J. Eur. Union. L 226/83–127 (2004)
44. The European Parliament and the Council of the European Union: Corrigendum to Directive 2004/41/EC of the European Parliament and of the Council of 21 April 2004 repealing certain directives concerning food hygiene and health conditions for the production and placing on the market of certain products of animal origin. Off. J. Eur. Union. L 195/12–15 (2004)
45. The European Parliament and the Council of the European Union: Regulation (EU) No 1169/2011 of the European Parliament and of the Council of 25 October 2011. Off. J. Eur. Union. L 304/18–63 (2011)
46. The Council of the European Union: Council Directive 2006/112/EC of 28 November 2006. Off. J. Eur. Union. L 347/1–118 (2006)
47. O'Connor, C., Gheoldus, M., Jan, O.: Comparative Study on EU Member States' legislation and practices on food donation, Final report (2014)
48. Downing, E., Kennedy, S., Fell, M.: Food Banks and Food Poverty. House of Commons Library. SN06657. Libr. House Commons. (2014)
49. Gov.uk: Supplying and using animal by-products as farm animal feed. https://www.gov.uk/guidance/supplying-and-using-animal-by-products-as-farm-animal-feed. Accessed November 2015
50. The European Comission: Commission Regulation (EU) No 142/2011 of 25 February 2011. Off. J. Eur. Union. L **54**, 1–254 (2011)
51. European Comission: Reference document on Best Available Techniques in the slaughterhouses and animal by-products industries (2005)
52. The Secretary of State: The Animal By-Products (Enforcement) (England) Regulations 2013. Statut. Instruments (2013)
53. Department for Environment, Food and Rural Affairs (Defra): Controls on Animal By-Products: Guidance on Regulation (EC) 1069/2009 and accompanying implementing Regulation (EC) 142/2011, enforced in England by the Animal By-Products (Enforcement) (England) Regulations 2011 (2011)
54. Gov.uk: Guidance for the animal by-product industry. https://www.gov.uk/government/collections/guidance-for-the-animal-by-product-industry. Accessed October 2015
55. Gov.uk: Using leftover milk and milk products as farm animal feed. https://www.gov.uk/guidance/using-leftover-milk-and-milk-products-as-farm-animal-feed. Accessed October 2015
56. Gov.uk: How to operate an animal by-product (ABP) processing facility. https://www.gov.uk/guidance/how-to-operate-an-animal-by-product-abp-processing-facility. Accessed November 2015
57. European Commission (EC): Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002 on undesirable substances in animal feed. Off. J. Eur. Union. L140, 10–21 (2002)
58. The European Parliament and the Council of the European Union: Regulation (EC) No 1831/2003 of the European Parliament and of the Council of 22 September 2003. Off. J. Eur. Union. L 268/29–42 (2003)
59. The European Parliament and the Council of the European Union: Regulation (EC) No 767/2009 of the European Parliament and of the Council of 13 July 2009. Off. J. Eur. Union. L 229/1–28 (2009)
60. The Secretary of State: The Animal Feed (England) Regulations 2010. Statut. Instruments (2010)
61. Food Standards Agency (FSA): Animal feed legislation and guidance. http://www.food.gov.uk/business-industry/farmingfood/animalfeed/animalfeedlegislation. Accessed November 2015
62. Gov.uk: Using animal by-products at compost and biogas sites. https://www.gov.uk/guidance/using-animal-by-products-at-compost-and-biogas-sites. Accessed December 2015
63. Biogas-info.co.uk: Regulation. http://www.biogas-info.co.uk/about/regulation/
64. Waste & Resources Action Programme (WRAP): Quality Protocol. Compost. End of waste criteria for the production and use of quality compost from source-segregated biodegradable waste
65. Department for Environment, Food and Rural Affairs (Defra),: Incineration of Municipal Solid Waste. (2013)
66. European Commission: Reference document on the Best Available Techniques for Waste Incineration. Integr. Pollut. Prev. Control. (2006)
67. Santos, M., Jiménez, J.J., Bartolomé, B., Gómez-Cordovés, C., Del Nozal, M.J.: Variability of brewer's spent grain within a brewery. Food Chem. **80**, 17–21 (2003)
68. Mussatto, S.I., Dragone, G., Roberto, I.C.: Brewers' spent grain: generation, characteristics and potential applications. J. Cereal Sci. **43**, 1–14 (2006)

69. Aliyu, S., Bala, M.: Brewer's spent grain: a review of its potentials and applications. Afr. J. Biotechnol. **10**, 324–331 (2013)
70. Environmental Protection Agency: BAT Guidance Note on Best Available Techniques for the Brewing. Malting & Distilling Sector, Wexford (Ireland) (2008)
71. Statutory Instruments: The Food Information Regulations 2014 (2014)
72. Ferraz, E., Coroado, J., Silva, J., Gomes, C., Rocha, F.: Manufacture of ceramic bricks using recycled brewing spent Kieselguhr. Mater. Manuf. Process. **26**, 1319–1329 (2011)
73. Diatomaceous Earth. https://www.diatomaceousearth.com/. Accessed March 2016
74. The Guardian: "It"s like eating a hedgerow': why do hop shoots cost €1,000 a kilo? http://www.theguardian.com/lifeandstyle/wordofmouth/2015/may/18/its-like-eating-a-hedgerow-why-do-hop-shoots-cost-1000-a-kilo. Accessed March 2016
75. European Commission: Reference document on Best Available Techniques in the food, drink and milk industries (2006)
76. Department for Environment, Food and Rural Affairs (Defra),: Feeding catering waste to farmed animals is ILLEGAL., London (UK)
77. Stuart, T., Miers, T., Wahaca: The pig idea. http://thepigidea.org/. Accessed March 2016

Appendix 7: Conference paper

Optimising industrial food waste management

This paper has been published in *Procedia Manufacturing* and presented by Guillermo Garcia-Garcia at the 14th Global Conference on Sustainable Manufacturing on 3-5th October 2016 in Stellenbosch, South Africa.

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 8 (2017) 432 – 439

Procedia MANUFACTURING

14th Global Conference on Sustainable Manufacturing, GCSM 3-5 October 2016, Stellenbosch, South Africa

Optimising industrial food waste management

Guillermo Garcia-Garcia[a], Elliot Woolley[a,]*, Shahin Rahimifard[a]

[a]*Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University, LE11 3TU, UK*

Abstract

Global levels of food waste are attracting growing concern and require immediate action to mitigate their negative ecological and socio-economic ramifications. In the developed world, of the order of 20-40% of food waste is generated at the manufacturing stage of supply chains and is often managed in non-optimised ways leading to additional environmental impacts. This research describes a novel decision-support tool to enable food manufacturers to evaluate a range of waste management options and identify the most sustainable solution. A nine-stage qualitative evaluation tool is used in conjunction with a number of quantitative parameters to assess industrial food waste, which is then used to generate performance factors that enable the evaluation of economic, environmental and social implications of a range of food-waste management alternatives. The applicability of this process in a software-based decision-support tool is discussed in the context of two industrial case studies.

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing
Keywords: food waste; waste management; sustainability; food manufacturing

1. Introduction

Achieving global food security is a challenge that necessitates a set of actions to be established and accomplished by numerous actors, including supranational organisations, governments, non-governmental organisations, food companies, retailers and consumers. One approach to increase food availability for societies with low economic incomes is to reduce food-waste volumes and redirect surplus food to people in need. It is estimated that just 25% of the global food waste would be enough to feed all the hungry people worldwide [1].

* Corresponding author. Tel.: +44 (0)1509 225410.
E-mail address: E.B.Woolley@lboro.ac.uk

Peer-review under responsibility of the organizing committee of the 14th Global Conference on Sustainable Manufacturing
doi:10.1016/j.promfg.2017.02.055

In the UK, most food waste is generated at only two stages of the supply chain: during manufacture and at the consumption stage. Currently, several initiatives seek into raise consumer awareness of the costs of food waste and provide advice on how to prevent food from becoming waste (e.g. Love Food Hate Waste [2]). However, there are fewer such joint attempts to reduce manufacturers' food waste and therefore food companies usually must identify and implement their own waste management and prevention solutions. Consequently, the food industry often manages its food waste in non-optimised ways, basing decisions on a limited number of factors such as costs, availability of waste management facilities and resource requirement to implement the solution. Additionally, large proportions of industrial food waste are unavoidable [3], which are commonly known as food by-products, implying food-waste management is necessary rather than preventive measures in some cases. Food-waste management alternatives (FWMAs) in the UK food industry have been quantified [4,5], as can be seen in Fig. 1, concluding that most of the industrial food waste in the UK cannot be reduced (i.e. it is unavoidable) and a range of different FWMAs are required, covering all the levels of the food-waste management hierarchy. Currently, around half of the food waste (including inedible materials) in the UK supply chain is produced at the manufacturing stage [4].

There is limited (and less reliable) information available for food waste generated at the manufacturing sector in the rest of European countries [6]. An approximate proportion of industrial food waste and by-products in supply chains of some large developed areas of the world is estimated in Table 1. It can be concluded that, in spite of the high variability, manufacturers contribute significantly to food waste quantities in the developed world. It must be also noted that different definitions and methodologies to quantify food waste are used in different regions. A harmonised methodology to quantify food waste in the supply chain, which should be followed to compare results of different countries, has been recently published by FUSIONS [7]. The high variability on food-waste proportions in the industrial stage of developed nations' supply chains can be explained by the size of the food-industry sector in the region, type of food produced (e.g. perishable foods or preserved foods), different regulations and government encouragement to reduce food waste, etc.

As a result, an increasing number of articles have been published to address this problem and propose software solutions or decision-support tools. Chang *et al.* [8] published an extensive review of simulation and optimisation models for solid waste management developed before 2010, highlighting the lack of a whole waste-management cycle approach. Relevant decision-support tools focused on sustainability issues of waste management have been proposed by various authors [9-11]. Karmperis *et al.* discusses different decision-support models with a focus on the applicability of game-theoretic approaches [12]. Soltani *et al.* also explores game-theoretic methods and introduces a weighing system to assess impacts of waste-to-energy technologies [13]. Additional research in this area has been

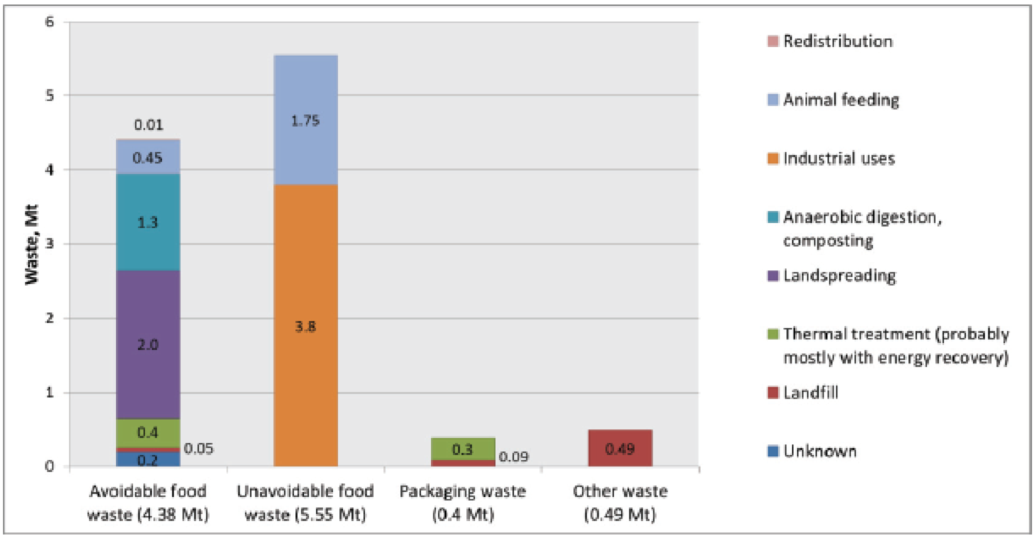


Fig. 1. Quantification of food-waste management alternatives (FWMAs) in the UK food industry. Data from WRAP [4,5]

carried out by Wang *et al.* applying a fuzzy-stochastic programming approach [14] and Rojo *et al.* [15] using a dynamic waste management approach. On the other hand, Hannan *et al.* reviewed recent developments of existing information and communication technologies (ICT) and their usage in solid waste management, which could facilitate data collection necessary for the decision-making with regard to waste management [16]. The authors believe this recently highly-populated area of research will benefit from a holistic approach that will serve to identify the most relevant attributes and their interrelationships to model food-waste management systems.

Table 1. Proportion of industrial (edible and inedible) food waste in food supply chains of some large developed areas of the world. [a]The European Commission does not include agricultural food waste into its calculations. [b]Includes industrial food by-products (i.e. unavoidable waste) which WRAP does not consider as food waste. [c]Does not include animal feeding or materials sent for biochemicals processing.

	Food waste in the supply chain, Mt	Industrial food waste, Mt	Percentage of total food waste generated at the manufacturing stage	References
US	67 – 134	20	15 – 30%	[17,18]
Japan	18	3 – 4	17 – 22%	[19]
Germany[a]	12.3	1.85	15%	[20]
France[a]	8.59	0.63	7%	[20]
Italy[a]	5.66	10.5	54%	[20]
UK[b]	19.25	9.93	52%	[4]
EU-27[a]	89.2	34.8	39%	[20]
EU-28[c]	87.6	16.9	19%	[21]

This paper outlines a novel decision-making procedure that can be used to address food-waste management issues from a broader perspective, considering direct and indirect ramifications of different possible solutions. It can be used as a framework with the following structure: a definition of parameters, data collection to value the aforementioned parameters, processing of information using mathematical models and the generation of a recommendation to increase sustainability of food-waste management. The procedure has been designed with the aim to be universally applicable, for all types of food waste, and considering five different waste-management alternatives. The links between different attributes are discussed and the practicality of this process in a software-based decision-support tool is explained in this paper. Two industrial case studies are used as samples to test the applicability of the proposed decision-making process.

2. Research methodology

In order to improve waste-management practices in the food industry a sound understanding of various elements involved in the process is needed:

1. Food waste: to comprehend characteristics of raw material to be managed (i.e. food waste).
2. Food-waste management alternatives (FWMAs): to be aware of the available waste management options and understand their performance.
3. Sustainability ramifications: to recognise ecologic and socio-economic consequences of different waste management practices.

This scheme, as described in Fig. 2, incorporates the determination of qualitative and quantitative parameters to estimate characteristics of food wastes, variables to model waste management processes and company status, factors to evaluate the performance of waste management practices, and key sustainability indicators to assess ramifications of FWMAs. The assessment of these indicators will help to select a tailored waste management practice that optimises the outputs generated.

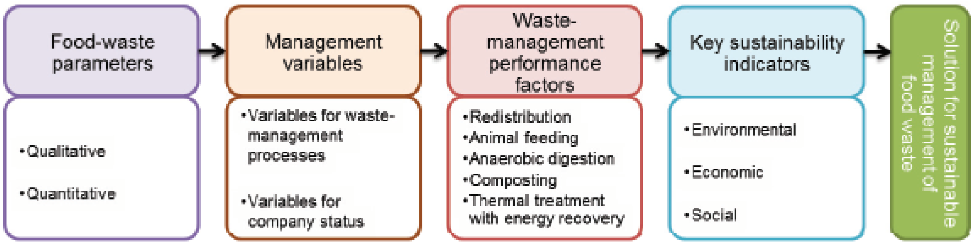


Fig. 2. Decision-making process and attributes to select sustainable solutions for food-waste management.

The first stage of the decision-making process is the selection of the relevant attributes to understand the aforementioned elements, which needs adjustments for each particular case. For instance, in order to treat milk waste the pH value is necessary, as opposed to meat waste, where the carbon-nitrogen relation (C:N) is more relevant. Secondly, the attributes identified must be linked to each other in a way that interrelationships are built. This necessitates a mathematical-modelling process that enables the estimation of an attribute's value through previously-obtained values of other attributes, e.g. the composition of toxic gases emitted to the atmosphere can be estimated knowing the characteristics of both food waste and the incineration process utilised. Thirdly, for the attributes that cannot be estimated through calculations from other attributes data must be collected, e.g. the carbohydrate content of food waste cannot be calculated from other attributes and therefore must be obtained from databases, previously published research or using analytical methods. Finally, the sustainability values generated for each FWMA are compared using a pre-established criterion. Combining these indicators allows a solution for sustainable food-waste management to be proposed. The key attributes identified to complete the first stage of this process are classified and characterised in the following sections.

The attributes needed to model waste management performance are dependent on the different FWMAs. In this work, the following FWMAs are considered: redistribution for human consumption, animal feeding, anaerobic digestion, composting and thermal treatments with energy recovery. The following FWMAs fall out of the scope of this paper: industrial uses, as its assessment will be needed for each individual food-waste type; and landspreading, thermal treatments without energy recovery and landfilling, because other possibilities are always prioritised due to their larger benefits.

3. Stages of the decision-making procedure

This section defines the data needed to characterise FWMAs. Each of the stages of the process is described, and the most relevant parameter, variable, factor and indicator of each type is identified and classified in Table 2.

Table 2. Examples of parameters, variables, factors and indicators to model food-waste management alternatives. FWMA, food-waste management alternative; R, redistribution for human consumption; AF, animal feeding; AD, anaerobic digestion; C, composting; and TT, thermal treatment with energy recovery.

	FWMA	Example of parameter, variable, factor or indicator	Example of value or unit	References
Qualitative parameters	R	Edibility	Edible / Inedible	[22]
Quantitative / Primary parameters	R, AF, AD, C, TT	Flow rate	(kg or m^3)/day	
Quantitative / Secondary parameters	AD, C, TT	Volatile solids (VS)	% of total solids (TS)	[23-25]
Process variables	AD, C, TT	Temperature	°C	[23-25]
Company variables	C	Pile size available	cm high, m wide	[26]
Performance factors	AD	Methane yield	L/(g VS)	[23]
Environmental indicators	R, AF, AD, C, TT	Greenhouse gas emissions	(kg CO_2 eq)/day	[27]
Economic indicators	R, AF, AD, C, TT	Economic income	£/month	
Social indicators	R	Feasibility to redistribute	Yes / No	

3.1. Parameters to estimate characteristics of food wastes

Food wastes are very diverse in their characteristics and composition. In this paper, all types of food waste that generates an economic cost or smaller benefit than predicted to the food business are considered, for instance unavoidable food waste and surplus food that could not be sold and so sent for redistribution to people in need or animal feeding. Packaging waste is only considered when it contains a food product (i.e. packaged food), but not separately.

Parameters to estimate characteristics of food wastes are classified into two categories (qualitative and quantitative parameters) and two sub-categories (for quantitative parameters, primary and secondary parameters), which are defined below and exemplified in Table 2.

Qualitative parameters have Boolean values and do not refer to a numerical value. A set of nine parameters, from Garcia *et al.* [23], are used in this research: edibility, state, origin, complexity, animal-product presence, treatment, packaging, packaging biodegradability and stage of the supply chain. An assessment of these characteristics provides initial guidance to select the most appropriate FWMA.

Quantitative parameters provide more specific and quantitative information about the characteristics of the food waste and are further classified in primary and secondary parameters as explained below:

- **Primary parameters** cannot be determined by other parameters. In order to obtain the value for primary parameters, experimental analysis, review of published literature or data collection from databases must be carried out. The values of primary parameters are intrinsic to the type and quantity of food waste under consideration, e.g. chemical composition.
- **Secondary parameters** can be calculated using values of primary parameters. In order to do so, mathematical relations must be built between secondary and primary parameters. Additionally, secondary parameters can be also obtained from experimental analysis, published literature or databases. Secondary parameters must be defined when considering different FWMAs, e.g. volatile fatty acids (which depend on fat content and composition) when assessing anaerobic digestion of food waste.

Some of the parameters described in this section are also relevant to evaluate the performance of the processes, e.g. the final pH and the lowest pH gives information about the yield of the composting process [28]; additionally the value of some parameters can be corrected during the treatment (e.g. addition of a buffer to control pH in the anaerobic digester) and therefore can be also considered waste-management processes variables. These types of parameters should be monitored during the process and evaluated at the end of the treatment as performance factors.

3.2. Variables to model waste management processes and company status

In addition to parameters based on food-waste characteristics, there are a number of variables which depends on other factors (i.e. external variables). They can be classified in two large categories: waste-management processes and company status variables. These categories are defined below and exemplified in the Table 2.

Waste-management processes variables need to be defined in order to evaluate the performance of the different alternatives, e.g. the temperature in the bioreactor is a key variable in order to obtain the maximum amount of biogas in an anaerobic digester. Clearly, the variables must be different for each FWMA considered. The values of these variables must be determined for each batch and type of food waste treated, since optimum values are unlike for different feedstocks (e.g. solid and liquid food waste) and situations (e.g. different levels of ripeness for the same type of food will cause variations in chemical compositions of the waste). As justified in Section 2, the following FWMAs are studied in this research: redistribution for human consumption, animal feeding, anaerobic digestion, composting and thermal treatments with energy recovery.

Some of the waste-management process variables are also relevant to evaluate the performance of the processes, e.g. the concentration of oxygen in the composted material [26]. This type of parameters should be monitored during the process and evaluated at the end of the treatment as performance factors.

Company status variables will not change from batch to batch as they are constant for a certain food company (i.e. fixed variables). For instance, the type of equipment to treat food waste available in the factory, or the distance to waste processors that take charge of the waste will generally remain unchanged. Clearly, these variables may also change over longer periods, e.g. new equipment can be purchased, but these variables will be considered fixed variables as the time to implement the changes is longer than the time given to manage food waste. When the variables (or their values) change, they will have to be amended in the model.

3.3. Factors to evaluate the performance of waste management practices

Once the aforementioned data has been collected and introduced in the tool, the performance of the different FWMAs can be estimated through a bespoke modelling of the different processes. For this purpose, firstly a set of factors to evaluate the performance of waste management practices must be defined for each FWMA considered. For instance, for anaerobic digestion the amount of biogas and its methane content will be the most relevant factors (as illustrated in Table 2). Secondly, these factors will have to be linked to the parameters and variables described in Sections 3.1 and 3.2, in a way that mathematical connections are formulated. As a result, the value of these factors can be calculated using previously assessed parameters and variables.

3.4. Key sustainability indicators to assess ramifications of FWMAs

In order to compare the results obtained from different FWMAs, their performance factors must be first converted into comparable indicators. Since the aim of this research is to increase the sustainability of food-waste management, the indicators chosen are associated to the three pillars of sustainability: environmental, economic and social ramifications, as described below and exemplified in Table 2.

Environmental indicators evaluate the impact on the environment (e.g. air, water, soil) of the different FWMAs. These impacts are generally negative (e.g. toxic gases emitted), but can also be positive in certain occasions (e.g. use of waste for the removal of pollutants in wastewater).

Economic indicators are used to assess the economic result from food-waste management, which can be either positive (economic benefit obtained from management of the waste) or negative (economic cost to dispose of the waste). FWMAs with worse economic output than currently-followed alternatives can be discarded at this stage.

Social indicators incorporate social considerations not addressed with environmental and economic indicators. They can also be either positive (e.g. decrease in food prices) or negative (e.g. increased taxes). Because of the complexity and vast variety of potential social ramifications from food-waste management, the social analysis undertaken in this research is focused only on feasibility to redistribute food fit for human consumption.

Again, mathematical models are needed to link the key sustainability indicators defined with the various factors to evaluate the performance of waste management practices. It must be noted that the sustainability indicators refer to the ramifications generated since the moment the food waste is produced until the management of the waste is finished (including transportation). Impacts related to the production of the food, its harvesting, storage, manufacturing, etc., have not been considered, as they will not influence the decision-making to manage food waste because they have already happened before food waste was generated. Therefore, a life-cycle approach was not appropriate for this paper.

4. Applicability of the model in a software-based decision-support tool and case studies

The parameters, variables, factors and indicators described in the previous sections can be used to model different solutions for food-waste management. Incorporating these considerations into a software tool enables manufacturers to gain information on different FWMA performances and their ramifications, and as a result a selection of the most sustainable solution to manage each type of food waste can be made. This decision will be assisted by a decision-support tool system which will be part of the software program. Consequently, the software tool is envisaged to be used mainly by waste managers in food manufacturing companies or members of staff with similar roles and duties in the food sector. Due to the different backgrounds and the huge dissimilarities amongst different food manufacturers, the interface is intended to be simple and user-friendly.

The software will be based in Microsoft Excel spreadsheets and MATLAB. Once the computer program is started, the user will see windows where the data needs to be introduced. This will be done selecting a parameter from a list of options in a dropdown menu (e.g. "edible" for qualitative parameters) or typing a numerical value in a box (e.g. C:N ratio "25" for quantitative parameters). The user will have to add all relevant data for both qualitative and quantitative food-waste parameters, and for both waste-management processes variables and company status variables. In a future development of this research the software will incorporate a database with the most relevant food-waste parameters, therefore the user will just have to select the food waste to manage from a dropdown menu and its associated parameters will be added automatically to the system.

The software will work following the process shown in Fig. 2. Once the data is added to the program, the software processes the information for each FWMA and calculates the values for each waste-management performance factors identified, using a set of mathematical models built in the system. These mathematical models are collected from a review of state-of-art literature in the relevant technologies (i.e. FWMAs) considered. In the same way, additional mathematical models incorporated in the software will convert waste-management performance factors into sustainability indicators, thus the indicators used when assessing FWMAs will be alike and therefore comparable (e.g. greenhouse gas emissions). As a result, the decision can be made to maximise positive outcomes and minimise negative ramifications. The decision-support tool will be designed in a way that the indicators will be weighed according to their relevance in food-waste management decisions, e.g. prioritising particle emissions to odour, or prioritising economic ramifications to environmental impacts. This prioritisation criterion is subjective and variable; therefore the weighing of indicators will be open to be amended by the user according to their needs and judgement.

The approach and terminology explained in this work has been applied to study different types of food waste generated at the industrial sites of two leading UK food manufacturers: Molson Coors, a brewing company; and Quorn Foods, a manufacturer of meat alternatives. Several types of food waste were identified in both companies and one for each business was selected to illustrate the applicability of this work (Fig. 3). In Molson Coors, the most significant food waste is the spent grain removed after the mashing process, which accounts for about 85% of the total food waste generated at the plant. In Quorn Foods, food-product returns was selected due to its high use of resources, as this is the final product that has undergone all the production process but cannot be sold due to a number of reasons, such as packaging errors, incorrect formulation, etc. The most relevant parameters, variables, factors and indicators were identified for each type of food waste. This approach is useful to compare the performance of the alternatives followed to manage food waste and also to identify and analyse potential improvements and alternative options to manage food waste.

5. Conclusions

This research presents a decision-making procedure to optimise industrial food-waste management. A terminology and decision-making process has been defined, which includes the description and identification of the most relevant parameters, variables, factors and indicators to model FWMAs. The applicability of the model described in a software-based decision-support tool has been discussed, and the practicality of the approach has been

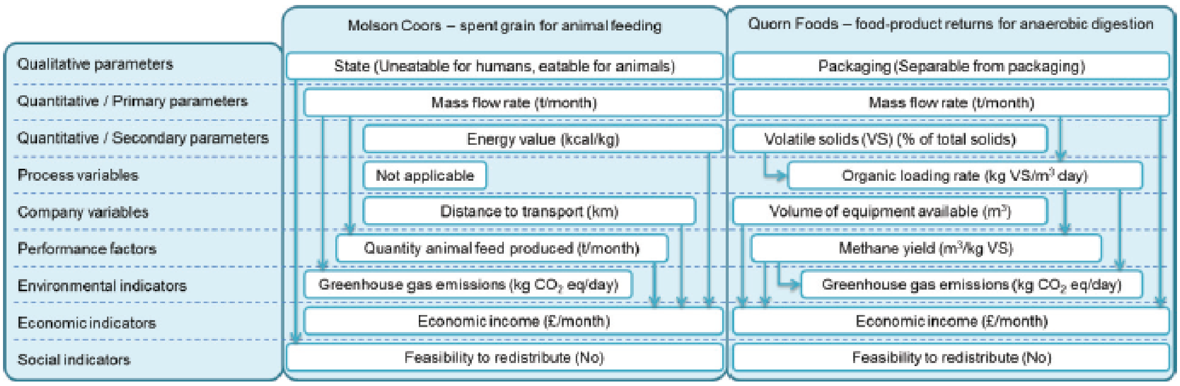


Fig. 3. Most relevant parameters, variables, factors and indicators to model food-waste management alternatives at Molson Coors and Quorn Foods manufacturing plants. The most relevant interrelationships between attributes are shown with arrows.

tested through two industrial case studies. Further work includes the identification of additional attributes which can be relevant to different FWMAs and the incorporation of their mathematical interrelationships into a software tool. As a result, the software tool will assess the environmental, economic and social performance of different solutions and inform the user of the best alternative to increase sustainability in food-waste management.

Acknowledgements

This research is funded by the Engineering and Physical Sciences Research Council (EPSRC) UK through the grant EP/K030957/1.

References

[1] FAO [Online]. www.fao.org/save-food/resources/keyfindings/en/. [Accessed: 4/4/2016].
[2] WRAP [Online]. www.lovefoodhatewaste.com. [Accessed: 5/4/2016].
[3] M. Bond, T. Meacham, R. Bhunnoo, T. Benton. Food waste within global food systems (2013). Global Food Security.
[4] WRAP. Estimates of food and packaging waste in the UK grocery retail and hospitality supply chain (2015).
[5] P. Whitehead, J. Parfitt, K. Bojczuk, and K. James. Estimates of waste in the food and drink supply chain (2013). WRAP.
[6] K.-R. Bräutigam, J. Jörissen, C. Priefer. The extent of food waste generation across EU-27: Different calculation methods and the reliability of their results, Waste Manag. Res., vol. 32 no. 8 (2014) pp. 683–694.
[7] FUSIONS. Food waste quantification manual to monitor food waste amounts and progression (2016).
[8] N.-B. Chang, A. Pires, G. Martinho. Empowering Systems Analysis for Solid Waste Management: Challenges, Trends, and Perspectives, Crit. Rev. Environ. Sci. Technol., vol. 41 no. 16 (2011) pp. 1449–1530.
[9] K. W. Harrison, R. D. Dumas, E. Solano, M. A. Barlaz, E. J. Downey Brill, S. R. Ranjithan. Decision support tool for life-cycle-based solid waste management, J. Comput. Civ. Eng., vol. 15, no. 1, (2001) pp. 44–58.
[10] P. Costi, R. Minciardi, M. Robba, M. Rovatti, R. Sacile. An environmentally sustainable decision model for urban solid waste management, Waste Manag., vol. 24 no. 3 (2004) pp. 277–295.
[11] J. den Boer, E. den Boer, J. Jager. LCA-IWM: A decision support tool for sustainability assessment of waste management systems, Waste Manag., vol. 27 no. 8 (2007) pp. 1032–1045.
[12] A. Karmperis, K. Aravossis, I. Tatsiopoulos, A. Sotirchos. Decision support models for solid waste management: Review and game-theoretic approaches, Waste Manag., vol. 33 no. 5 (2013) pp. 1290-1301.
[13] A. Soltani, R. Sadiq, K. Hewage. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making, J. Clean. Prod., vol. 113 (2016) pp. 388-399.
[14] S. Wang, G.H. Huanga, B.T. Yang. An interval-valued fuzzy-stochastic programming approach and its application to municipal solid waste management, Environ. Model. Softw., vol. 29 (2012) pp. 24-36.
[15] G. Rojo, M. Glaus, R. Hausler, V. Laforest, J. Bourgeois. Dynamic waste management (DWM): Towards an evolutionary decision-making approach, Waste Manag. Res., vol. 31 no. 12 (2013) pp. 1285-1292.
[16] M.A. Hannan, M. Abdulla Al Mamun, A. Hussain, H. Basri, R.A. Begum. A review on technologies and their usage in solid waste monitoring and management systems: Issues and challenges, Waste Manag., vol. 43 (2015) pp. 509-523.
[17] J. Bloom, American Wasteland. How America Throws Away Nearly Half of Its Food (and What We Can Do About It). Da Capo Press (2011).
[18] BSR. Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Wholesalers, April (2013).
[19] F. Marra. Fighting Food Loss and Food Waste in Japan (2013). Leiden University.
[20] European Commission (DG ENV). Preparatory Study on Food Waste Across EU 27 (2010).
[21] FUSIONS. Estimates of European food waste levels (2016).
[22] G. Garcia-Garcia, E. Woolley, S. Rahimifard. A Framework for a More Efficient Approach to Food Waste Management, Int. J. Food Eng., vol. 1 no. 1 (2015) pp. 65–72.
[23] R. Zhang, H. M. El-Mashad, K. Hartman, F. Wang, G. Liu, C. Choate, P. Gamble. Characterization of food waste as feedstock for anaerobic digestion, Bioresour. Technol., vol. 98 no. 4 (2007) pp. 929–935.
[24] J. I. Chang, J. J. Tsai, K. H. Wu. Thermophilic composting of food waste, Bioresour. Technol., vol. 97 no. 1 (2006) pp. 116–122.
[25] I. I. Ahmed, A. K. Gupta. Pyrolysis and gasification of food waste: Syngas characteristics and char gasification kinetics, Appl. Energy, vol. 87 no. 1 (2010) pp. 101–108.
[26] L. Cooperband. The Art and Science of Composting. A resource for farmers and compost producers (2002).
[27] E. den Boer, F. Brouwer, A. Schroten, H. van Essen. Are trucks taking their toll? The environmental, safety and congestion impacts of lorries in the EU (2009).
[28] J. I. Chang, Y. J. Chen, Effects of bulking agents on food waste composting, Bioresour. Technol., vol. 101 no. 15 (2010) pp. 5917–5924.

Appendix 8: Book chapter

Forging New Frontiers in Sustainable Food Manufacturing

This article has been accepted for publication in the book *Smart Innovation, Systems and Technologies* and presented as a keynote paper by Prof Shahin Rahimifard at the 4th International Conference on Sustainable Design and Manufacturing on 26-28th April 2017 in Bologna, Italy.

This paper cannot be included in this appendix due to copyright reasons. The publisher website can be found at this link: http://www.springer.com/series/8767.