sustainability

MDPI

Article

Identification and Analysis of Attributes for Industrial Food Waste Management Modelling

Guillermo Garcia-Garcia [1], **Elliot Woolley** [2,*] and **Shahin Rahimifard** [1]

[1] Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Loughborough University, Epinal Way, Loughborough, Leicestershire LE11 3TU, UK; G.Garcia-Garcia@lboro.ac.uk (G.G.-G.); S.Rahimifard@lboro.ac.uk (S.R.)
[2] Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Epinal Way, Loughborough, Leicestershire LE11 3TU, UK
* Correspondence: E.B.Woolley@lboro.ac.uk; Tel.: +44-(0)1509-225410

Received: 15 March 2019; Accepted: 20 April 2019; Published: 25 April 2019

check for updates

Abstract: Due to the large quantities of food waste generated by manufacturers and the associated environmental impact of these waste streams, improving food waste management is vital for achieving a more sustainable food system. Management of food waste can be complex and the most appropriate methods may not always be selected. There are a range of aspects to consider in order to select the most sustainable option to manage food waste, such as the specific type of food waste generated, waste management options available, characteristics of food companies that generate food waste, features of the waste management processors that will manage it, and the sustainability implications of dealing with the food waste. To support food waste management decision making, this paper presents a modelling procedure to assist in identifying what type and range of information is needed to model food waste management systems, allowing the user to follow a systematic methodology to make more informed decisions. This procedure is based on the identification and analysis of qualitative and quantitative attributes necessary to model food waste management and an assessment of their relationships. Specifically, it describes a process to ensure that all relevant attributes are considered during the decision-making process. A case study with a large UK food and drink manufacturer is used to demonstrate the applicability and usefulness of this procedure. In conclusion, the systematic procedure presented in this paper provides a methodology to identify opportunities to improve the sustainability of industrial food waste management. The data obtained can be used to further undertake a life-cycle assessment study and/or to apply existing socio-economic methodologies to thoroughly assess impacts and benefits of food waste management.

Keywords: food waste; sustainability; waste management; sustainability indicators; ecological modelling

1. Introduction

It is largely known that the efficiency of the food production industry is far from perfect due to the high levels of food waste (FW) it generates. Managing this FW causes food companies significant economic costs and increases the environmental impact of the company. Although preventing FW generation is always the ideal solution to tackle this issue, this is frequently not possible, since large amounts of industrial FW are unavoidable, i.e., they are by-products. In these cases, when FW cannot be reduced, reactive approaches to manage FW in the best possible way are needed.

Fortunately, there are a number of approaches and solutions to manage these waste materials. Frequently, the challenge is to identify the solution that will maximise benefits and reduce negative ramifications. At an industrial level, the feasibility of applying waste management solutions often depends on the size, economy, and autonomy of a company, thus low-cost solutions applied to what is perceived to be a low-cost problem are common. When planning to valorise FW materials to get an additional economic income or to reduce environmental impacts, food waste management (FWM) is generally perceived as a complex issue without a 'one-size-fits-all' optimal solution. Methodologies and approaches to better enable the identification of the optimal solution and improve the sustainability performance of FWM are largely beneficial.

In this context, management of FW is an active research area that has significantly developed over recent years [1]. This vibrant research field aims to find more sustainable ways to manage FW, i.e., addressing the triple bottom line impacts whilst maximising potential benefits. There are many examples of research publications which seek to improve FWM, but they have typically only sought to improve one domain of sustainability: environmental, economic, or social ramifications [2,3]. More recent research aims to expand the scope and consider two or three pillars of the triple bottom line. For instance Münster et al. (2015) [4], Ahamed et al. (2016) [5], and Martinez-Sanchez et al. (2016) [6] consider economic and environmental ramifications of FWM. Along these lines, a framework to assess the sustainability performance of agri-food waste management, including by-product valorisation, that considers environmental, economic, and social indicators, is being developed as part of the AgroCycle project [7]. Furthermore, the recently developed life-cycle sustainability assessment (LCSA) methodology also aims to consider the three pillars of the triple bottom line for sustainability assessments [8]. It is expected that LCSA will be further developed in the next years [9] so then it can become a standardised methodology to assess the sustainability performance of industrial practices, including FWM.

With regard to assessing environmental impacts, life-cycle assessment (LCA) has become a popular methodology and its use has been increasing not only in research applications but also in the industrial sector. Although the LCA methodology has significantly been developed in recent years, and the quantity and quality of LCA data has also clearly increased, there are still some weaknesses and challenges in its application. For instance, the completeness, preciseness, and level of update of different databases vary significantly. In the field of solid waste management systems, ecoinvent remains the most used database for LCA studies [10], but other databases which update less frequently and contain less information are also commonly used. Thus, the LCA community would significantly benefit from more comprehensive databases. Also, a study of the relationships between each datum entry in the database, within the process studied or related to other process in the database, could aid in the optimisation of FWM models. Similar conclusions can be obtained from the analysis of other environmental assessment tools and economic and social methodologies.

To address these issues, this paper aims to bring two important topics closer in the sustainability field: LCA and FWM. It does so by presenting a FWM modelling procedure (FWMMP) that consists of a systematic methodology to estimate environmental, economic, and social implications of FWM.

2. Attributes to Model Food Waste Management

The FWMMP described in this paper provides a standardised way to collect and analyse data in order to support industrial decision making. Quantitative attributes are used to model FWM, which can be used to accurately estimate quantitative outcomes of using a particular food waste management solution (FWMS) selected by the food production company. Importantly, the described FWMMP can be used to compare alternative FWMSs, reassuring users that the option selected is the most sustainable based on the assessment criteria. The following five FWMSs were considered when developing the FWMMP: redistribution, animal feeding, anaerobic digestion, composting, and thermal treatment with energy recovery. Other potential solutions were excluded from the FWMMP presented in this paper, as justified by Garcia-Garcia et al. (2017) [11]: landspreading, thermal treatments without energy recovery and landfilling because other possibilities should be prioritised due to their better sustainability performance; industrial (non-food) utilisation of FW because of the enormous variety of options available, which would require a bespoke analysis for each individual scenario; and prevention, because this option would always be prioritised for edible FW, whereas it is not applicable to inedible FW. Nevertheless, the FWMMP user can always identify relevant attributes for other FWMSs, add them to the FWMMP, and analyse them following the methodology explained in this paper.

Table 1 shows the main stages of the FWMMP. For each stage, all attributes required for modelling must be identified and then evaluated. The attributes are classified as: qualitative and quantitative parameters to evaluate properties of FW, 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 more detailed explanation of these four stages and categories of attributes can be found in Garcia-Garcia et al. (2017) [11].

Table 1. Stages of the food waste management modelling procedure. Based on Garcia-Garcia et al. (2017) [11].

Food Waste Parameters				
Qualitative		Quantitative		
		Primary		Secondary
Management Variables				
Variables for food waste management processes		Variables for company status		
Food Waste Management Performance Factors				
Redistribution	Animal feeding	Anaerobic digestion	Composting	Thermal treatment with energy recovery
Sustainability Indicators				
Environmental indicators		Economic indicators		Social indicators

A list of relevant attributes was compiled after undertaking an extensive study of the five FWMSs considered. This list, which contains 175 attributes, can be interpreted as a catalogue of data needed to assess FWM scenarios, including data needed for the model (input) and results obtained that allow sustainable decision making (output). Due to the large size of the list generated, it can be found as Supplementary Material of this paper (Supplementary Material—1. List of Attributes).

The attributes needed to model the processes and characterise raw materials were identified and classified according to the FWMMP. Redundant attributes were removed or assimilated into other attributes. Each attribute was independently assessed and their inclusion in the list of attributes was decided based on their relevance to support the aim of the FWMMP. Hence, attributes which were found only in a very small number of publications (e.g., lowest pH achieved during composting) or were not substantially relevant to FWM (e.g., N_2 content in biogas), were discarded. The list of attributes is not intended to be exhaustive but rather determinative and practical. It includes the attributes needed to undertake detailed modelling of FWM, based on a thorough analysis of the five possible FWMS considered. The user of the FWMMP is able to add or remove attributes in the lists to adapt it to the user's specific needs.

The list of attributes is particularly helpful when a new FW that needs managing is identified, as solutions previously used with other FWs will often not be appropriate for new FWs. As Bisinella et al. (2017) [12] demonstrated, the composition of the waste to be treated largely affects both LCA results and their uncertainty, in a direct way (input-specific emissions) and also indirectly (process-specific emissions and background processes affected by the characteristics of the waste). In spite of this, there is no consensus yet on international standard methodologies to characterise waste [13,14]. Recently, the consortium formed in the AgroCycle project has recognised the influence of the physicochemical properties on the outcomes of treating agricultural FWs and started to address this issue by creating an inventory of such characteristics for different types of agricultural FW [15].

There are additional factors that complicate the analysis of FWM systems further, including considerations such as: the chemical composition of the same type of FW might vary depending on the time or location it was produced, the same technologies may perform with different efficiencies (e.g., due to different on-site conditions), and other factors outside of the FWM system may critically influence results (e.g., the importance of applying a more energy-efficient process varies depending on where the energy comes from, for instance coal or renewable sources) [16]. In all of these cases, a new analysis of the FW to be treated and potential FWMSs to be used would be needed. The FWMMP would support this task.

Due to the complexity of the FWMMP, it may not be practical for some users to apply it in its entirety, and they may prefer to use just some of the tools from the procedure. In the next section, an analysis of the relationships between attributes is presented, which simplifies the use of the FWMMP.

3. Relationships between Food Waste Management Attributes

This section analyses the attributes presented in the previous section and listed in Supplementary Material—1. List of Attributes in order to identify relationships between them. The exposure of relationships helps to highlight which attributes must be defined in order to obtain the data sought. The end of the section describes an approach to determine the attributes needed to assess unknown attributes and the optimal order of the assessment.

Figure 1 shows the sequence of application for the different tools explained in this section. The output of these tools is the obtention of information flow diagrams that highlight specific dependencies between different FWM attributes. For instance, there is a relationship between the 'particle size' of the raw material and 'compost production rate', since particle size affects the yield of the composting process. In this example, 'particle size' is an attribute needed to evaluate the value of a sought attribute (such as 'compost production rate'), which may initially be unknown, and similarly 'compost production rate' is dependent on 'particle size'.

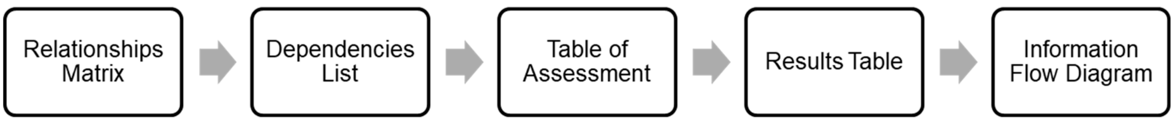

Figure 1. Integration of tools to obtain information flow diagrams.

3.1. The Relationships Matrix

Defining relationships between all possible attributes is not straight-forward and not practical because: (a) 175 attributes have been defined leading to 15,225 relationship pairs ((1752–175)/2) and, (b) each FWMS will present distinctive relationships that should be considered on a case-by-case basis. In addition, it is necessary to define different types of relationships between two paired attributes:

1. No relationship: both attributes assessed lack of any dependency to each other. For example, the 'density' of FW and the 'job creation' social indicator are not related, i.e., in order to calculate the value of one attribute the other one is not needed.
2. Indirect relationship: there is no mathematical connection between both attributes, although one attribute indirectly affects the possible values of the other attribute. This occurs when, for instance, the value of one variable limits the use of a FWMS, and therefore the value of the second attribute is affected. For example, 'energy/nutrient 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/nutrient value' of FW, their values can restrict the use of FW for animal feeding and therefore the need to assess 'energy/nutrient value'.
3. 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, 'carbohydrate content' of FW is needed to estimate the 'chemical oxygen demand' of the wastewater generated from FWM.

Clearly, instances of no relationship can be disregarded and due to the impracticality of assessing indirect relationships, only direct relationships are identified and presented in this paper. The presence or absence of relationships between attributes has been represented in a 175 × 175 matrix with 30,450 relationships. Relationships 'attribute A′ → 'attribute B′ and 'attribute B′ → 'attribute A′ needed to be considered separately as they represent different dependencies. These relationships were identified based on the authors' knowledge about the FWMSs studied. The complete relationships matrix can be found in Supplementary Materials with the name Supplementary Material—2. Relationships Matrices. Below, screenshots of two sections of the relationships matrix (Figures 2 and 3) are provided as small examples of the full matrix. A green tick denotes presence of direct relationship and a red cross absence of a direct relationship.

Relationships between food waste management attributes

	A	B	C	D	R	S	T	U	V	W	X
1					Food waste parameters						
2					Quantitative						
3					Primary parameters						
4					Vitamin content and composition	Other organic compounds	Inorganic content and composition	Moisture content	Biological hazard	pH	Particle size
71	Sustainability indicators	Environmental	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 2. Example 1: 24 × 7 matrix showing an analysis of 168 relationships between some quantitative primary FW parameters and environmental impact to air indicators.

In Figure 2, it can be observed that 'inorganic content and composition' affects all environmental impact to air indicators listed in this example, since presence of different inorganic compounds can largely affect the composition of gases obtained from a FWMS. 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 3, the attributes that affect 'quantity of food redistributed' and 'quantity of animal feed produced' are nearly the same, 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'.

	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	$[CH_4]$ 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/nutrient 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 3. Example 2: 29 × 7 matrix showing an analysis of 203 relationships between performance factors and FW parameters.

A relationship between two attributes is considered to exist even if it only exists for some FWMSs and not for others. 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 obtained 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.

Possible chemical reactions are considered in this analysis. For instance, nitrogen present in a particular FW (and measured with 'total Kjeldahl nitrogen' and/or 'total ammonia nitrogen') may react and create substances such as N_2O, NO_X, NH_3, and NO_3^-, which can pollute air, water, or soil. Therefore, when assessing chemical compounds that can be formed during the process (e.g., NH_3), the precise initial composition of a FW is needed (i.e., content of carbohydrate, fat, protein, and other molecules and elements) since this will have a bearing on 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 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.

Specific considerations that affect individual attributes can be found in the Supplementary Material—2. Relationships Matrices, in the sheet "Notes on specific relationships".

In its basic form the considerable size of the relationships matrix makes it cumbersome for use. Therefore, a number of actions have been taken to reduce its size and improve its usability. In all cases where a group of attributes are related to the same attributes, they have been combined. For instance, '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). Consequently, these attributes have been combined into one single attribute, namely 'CO_2, CH_4, NMVOC and PM < 10'. Doing this for all relevant cases, the combination of attributes allows a reduction in the size of the relationships matrix from a 175 × 175 matrix with 30,450 relationships to a 136 × 136 matrix with 18,360 relationships. This version of the relationships matrix can be found in the Supplementary Material—2. Relationships Matrices, in the sheet "Relationships Matrix (grouped)".

Additionally, an alternative version of the matrix has been developed to further reduce the size of the relationships matrix: the streamlined relationships matrix. Since the stage of the FWMMP with more attributes correspond to environmental indicators, this list 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 these indicators was undertaken considering the most commonly-used indicators to assess environmental impacts of FWM in the literature. This version of the relationships matrix can be found in the Supplementary Material—2. Relationships Matrices, in the sheet "Relationships Matrix (strml.)".

Similarly, the list of process and company variables has been reduced to include only the most relevant attributes. 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'. This version of the relationships matrix, with the reduced environmental indicators and process and company variables, can be found in the Supplementary Material—2. Relationships Matrices, in the sheet "Relationships Matrix (strml.2)".

The dimension of the "Streamlined 2" relationships matrix is 73 × 73 and contains 5256 relationships.

3.2. Dependencies Lists

Once all relationships between attributes have been found, there is a need to assess the dependencies between attributes. For instance, for animal feeding, the relationships matrix shows that 'energy/nutrient value' and 'economic value of solid material' are related, but not which attribute depends on the other. In this example, 'economic value of solid material' depend on 'energy/nutrient value', since the value of 'energy/nutrient value' is needed to quantify the value of 'economic value of solid material', and not the other way around. All dependencies for each relationship have been assessed and listed in the Supplementary Material—3. 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 ("Relationships Matrix (strml.)"). An example of a section of a dependencies list can be seen in Figure 4.

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, and are provided in Supplementary Material—3. Dependencies List, in their pertinent sheet. In each dependencies list, the attributes relevant to the FWMS assessed have been highlighted in red (as in Figure 4), because only those attributes are needed to model that FWMS. For instance, 'quantity of animal feed produced' is not needed to assess redistribution for human consumption and therefore is not highlighted in Figure 4.

Even with the specific list of attributes for each FWMS it is not always necessary to consider all relationships: some may be discarded for that particular analysis. 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. Hence, each dependency from each FWMS has been assessed independently to discard non-necessary dependencies. The discarded dependencies can be found in Supplementary Material—3. Dependencies List, in the sheet "List of exceptions".

	B	C	D	E	F
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 4. Section of the dependencies list for redistribution for human consumption showing dependencies to five attributes. In this example the first column means that 'state', 'quantity of food redistributed', and 'quantity of animal feed produced' depend on 'edibility'.

3.3. Dependencies Flowcharts

Dependencies flowcharts which show the dependencies between all attributes relevant to each FWMS have been generated based on the five dependencies lists explained in Section 3.2. The attributes have also been classified according to the FWMMP (shown in Table 1). The dependencies flowcharts are presented in Supplementary Material—4. Dependencies Flowcharts. The full version of the relationships matrix with combined attributes was used for redistribution and animal feeding, but, due to size limitations, the streamlined relationships matrix was used for anaerobic digestion, composting, and thermal treatment with energy recovery. It should be noted that for the latter three FWMSs, 'chemical oxygen demand (COD)', and 'total suspended solids (TSS)' have been combined into one attribute, since their dependencies are the same in the streamlined versions of the dependencies flowcharts.

The dependencies flowcharts are versatile. An attribute can be selected and the attributes that depend on it, identified. Alternatively, an attribute can be selected and it can be elucidated which attributes are required in order to assess that attribute.

3.4. Table of Assessment

It is important to be able to determine the attributes needed to assess a FWMS and also the attributes needed to assess unknown values of other attributes. This section describes a methodology for this purpose that has been designed in a way such that it can be used by any company or suitably knowledgeable person who manages FW, henceforth referred to as the 'user'. The methodology is intended to be applied each time a new FW is identified, or the user becomes aware of a change in the known/unknown attributes.

The main tool for this part of the FWMMP is the Table of Assessment. The Table of Assessment is built from the dependencies list, and it can used to obtain the results table, which in turn can be used to draw information flow diagrams, as shown in Figure 1.

The user starts the analysis using the Table of Assessment, which is a spreadsheet that contains one sheet for each FWMS. The Table of Assessment can be found in Supplementary Material—5. Table of Assessment. In each of the sheets, all attributes needed to model FWM for that particular FWMS are listed, which have been identified using the tables in Supplementary Material—1. List of Attributes. 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 Figure 5.

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

Figure 5. An example of a section of the table of assessment for redistribution for human consumption.

The dependencies lists and the dependencies flowcharts were both used to populate the 'list of attributes needed'. The specific methodology used to build the 'list of attributes needed' is depicted in Figure 6. 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' (the sheet of list of exceptions is in Supplementary Material—3. Dependencies List). This process should be repeated until all attributes relevant to the FWMS under consideration have been assessed, completing the 'list of attributes needed'.

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 which attributes should be used to calculate unknown attributes. The entire process, integrating all research presented in this paper, is explained below.

The process is initiated when the user identifies the FW to be analysed and chooses a potential FWMS to be used. The methodology presented by Garcia-Garcia et al. (2017) [17] can be used to guide this stage. After that, the user should 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 ('Y'), unknown ('N') and required ('R'), since not all attributes may be required for assessment by the user. An example of a section of the Table of Assessment, with the required information completed, can be seen in Figure 7. 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 materials', 'total emissions to air', 'CO_2', 'CH_4', 'NMVOC', 'PM < 10', and 'feeding people in need' 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.

Once the two columns of the Table of Assessment have been completed, the results table should be filled ("Results Table" sheet in Supplementary Material—5. Table of Assessment). An example of a results table for the example presented above can be seen in Figure 8. The user must identify 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'.

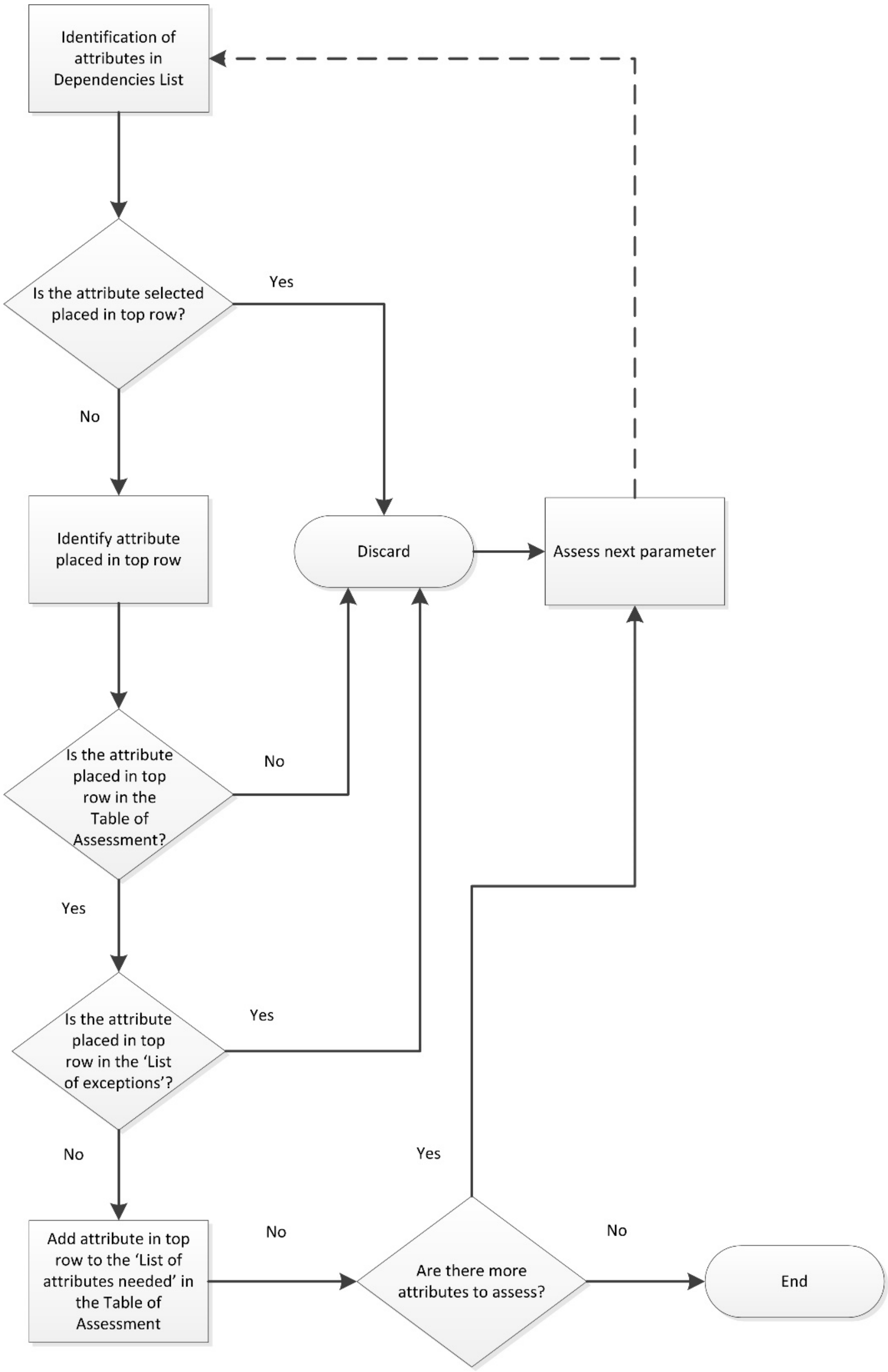

Figure 6. Methodology used to build the 'list of attributes needed' in the table of assessment.

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

Figure 7. 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 shown in the figure is divided into two parts.

Results Table					
n	Destiny attribute	Origin attribute			
3	Biological hazard	State			
2	State	Edibility			
1	Edibility	–			
4	Hazardous materials	State	Other organic compounds	Inorganic content and composition	Biological hazard
1	Other organic compounds	–			
1	Inorganic content and composition	–			
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		

Figure 8. Results table of the example presented in Figure 7.

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 the first place. For instance, in Figure 8 '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 Figure 7, 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 $n = 1$.

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 is 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 Figure 8 that 'hazardous materials' has 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 user can use the results obtained in Figure 8 to determine the attributes needed to assess unknown attributes and the required order of the assessment. This is represented in Figure 9, 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'. The use can draw information flow diagrams to more easily identify the attributes that must be defined and assessed to obtain the information pursued, and also support their evaluation by providing a structure for calculation steps, i.e., the order of the assessment. For instance, in Figure 9 there are four calculation steps needed to calculate values of all unknown required attributes, and the attributes that must be calculated in each of these steps are also shown in the information flow diagram. In summary, the user can utilise information flow diagrams to identify the specific information needed to model FWMSs and break down complex calculation processes into a step-by-step approach, gaining accurate and appropriate guidance to assess different FWM scenarios. The use of the information flow diagrams is the last step of the FWMMP as shown in Figure 1. After using the information flow diagrams to identify calculation steps and the order of the assessment, and the values of unknown required attributes are calculated, the data obtained can be used in an LCA study and/or to undertake socio-economic assessments of FWM.

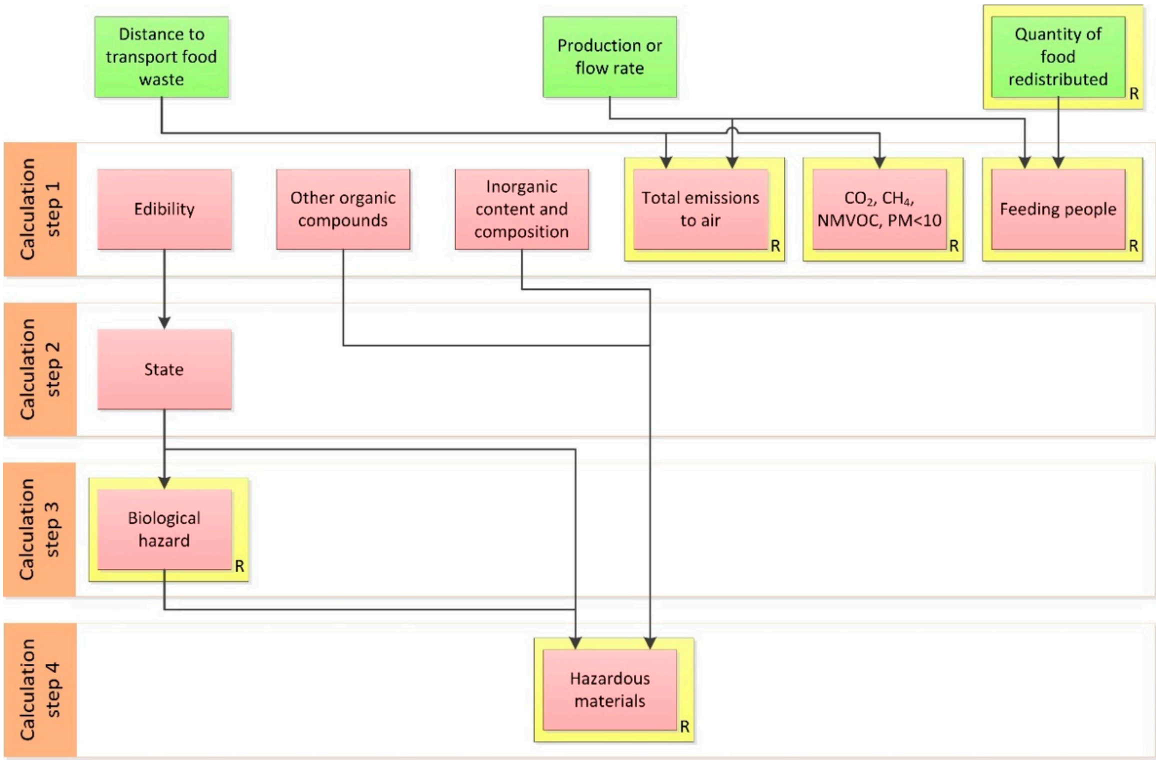

Figure 9. Information flow diagram built from Figure 8. Green attributes: known attributes, red attributes: unknown attributes, attributes in yellow R boxes: required attributes.

4. Case Study

The FWMMP has been applied to a case study within a large UK food and drink manufacturer: Molson Coors Brewing Co. (UK), Ltd. (Molson Coors), in order to demonstrate and evaluate the applicability of the research.

Three primary approaches were used to facilitate the collection of data: site visits, interviews, and questionnaires. Before the site visits email contact was used to identify interests of the company 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 company's headquarters in Burton upon Trent in Staffordshire took place to gain a better understanding of the FW generated. An in-person interview was held with the Product and Process Development Brewer of Molson Coors. During the interview, a questionnaire was used to systematically identify FW streams and collect relevant qualitative and quantitative data. Following the site visits and in-person interviews, further email contact was used to collect additional information.

The data presented in this chapter are original data provided by the food manufacturer, in addition to published data regarding 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. It should be noted that some of the data collected and generated is not reported here due to commercial sensitivities (e.g., economic performance of FWM).

Out of the FWs generated by Molson Coors, i.e., spent grain, waste beer, conditioning bottom, filter waste and trub, only the upgradeable FWs—identified by Garcia-Garcia et al. (2017) [17] as waste beer and filter waste—are considered in this section. The more sustainable, alternative FWMSs for both FWs are redistribution for human consumption and anaerobic digestion respectively, according to the aforementioned study. 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.

4.1. Waste Beer

The attributes needed to model redistribution for human consumption, according to Supplementary Material—1. List of Attributes, are listed in its Table of Assessment (Figure 10). The classification of attributes as known/unknown and required/non-required has been decided based on consultation with staff from Molson Coors and reasonable assumptions where 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.

Known attributes are those referring to general characteristics of beer and its manufacturing (e.g., 'edibility', 'density', and 'treatment'), quantity of waste beer generated and distance to transport it. Required attributes are related to the quantity of waste beer available for redistribution, 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 further attributes for each attribute to assess.

Once the Table of Assessment has been completed, a results table was prepared (Figure 11). This table 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 12) that represents the order of assessment for each attribute and the attributes needed for each assessment. 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, NO_X', 'TOC, dust, PM < 2.5', 'quantity of food redistributed', 'management cost', and 'feeding people'. 'State', 'biological hazard', and 'hazardous materials' are unknown attributes which must also be evaluated to be able to assess the 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	Edibility	Y	
	State	N	
	Treatment	Y	
Primary quantitative food waste parameters	Production or flow rate	Y	R
	Biological hazard	N	
	Other organic compounds	Y	
	Inorganic content and composition	Y	
Secondary quantitative food waste parameters	Hazardous materials	N	
	Density	Y	
Process and company variables	Distance to transport food waste	Y	
Performance factors	Quantity of food redistributed	N	R
Environmental indicators: impacts to air	Total emissions to air	N	R
	CO_2, CH_4, NMVOC, PM<10	N	R
	N_2O, NOx	N	R
	Total organic carbon (TOC), dust, PM<2.5	N	R
Environmental indicators: impacts to water			
Environmental indicators: impacts to soil			
Economic indicators	Management cost	N	R
Social indicators	Support of local economies	N	
	Job creation	N	
	Noise	N	
	Feeding people	N	R
	Traffic	N	

List of attributes needed									Known dependencies	Unknown dependencies
Edibility									1	
State										1
State	Other organic compounds	Inorganic content and composition	Biological hazard						2	2
Production or flow rate									1	
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
Distance to transport food waste	Production or flow rate								2	
Distance to transport food waste									1	
Distance to transport food waste									1	
Distance to transport food waste									1	
Production or flow rate	Distance to transport food waste	Quantity of food redistributed							2	1
Production or flow rate	Quantity of food redistributed								1	1
Production or flow rate	Quantity of food redistributed								1	1
Production or flow rate	Quantity of food redistributed	Distance to transport food waste							2	1
Production or flow rate	Quantity of food redistributed								1	1
Production or flow rate	Quantity of food redistributed	Density	Distance to transport food waste						3	1
								Total	25	12

Figure 10. Table of assessment 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 11. Results table for waste beer.

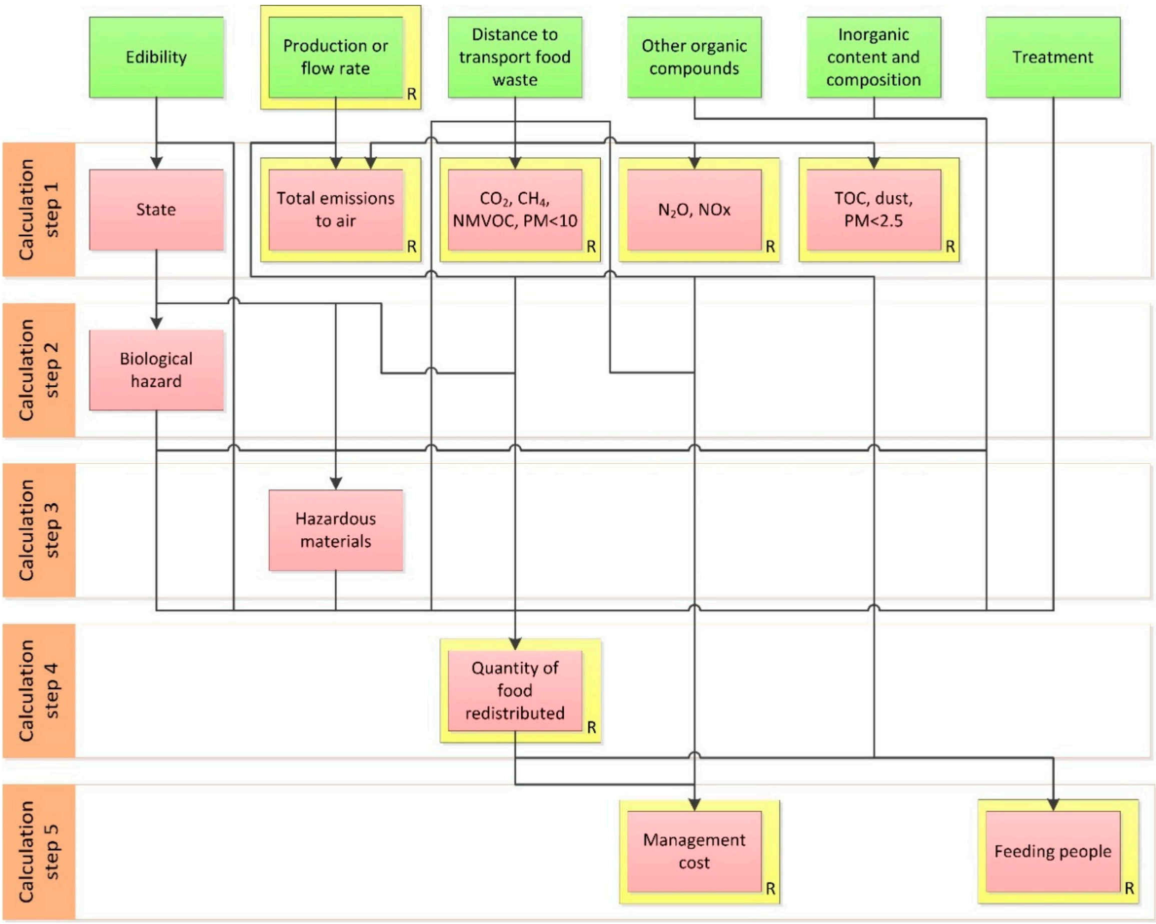

Figure 12. Information flow diagram for waste beer.

4.2. Filter Waste

The attributes needed to model anaerobic digestion, according to Supplementary Material—1. List of Attributes, are listed in the Table of Assessment (Figure 13). The classification of attributes as known/unknown and required/non-required has been decided following the same reasoning as for beer waste. 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 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 provides information about 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 Figure 13 this specific information has been excluded due to size limitations.

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	

Figure 13. Section of table of assessment for filter waste showing categories of attributes, attributes to asses, known/unknown attributes, and required attributes.

The results table for filter waste (Figure 14) shows the order (n) in which each attribute must be assessed, and the attributes needed for this assessment ('origin attribute').

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				
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					
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					
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					
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 14. Results table for filter waste.

Finally, the results table has been used to draw an information flow diagram (Figure 15) 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 of the required attributes.

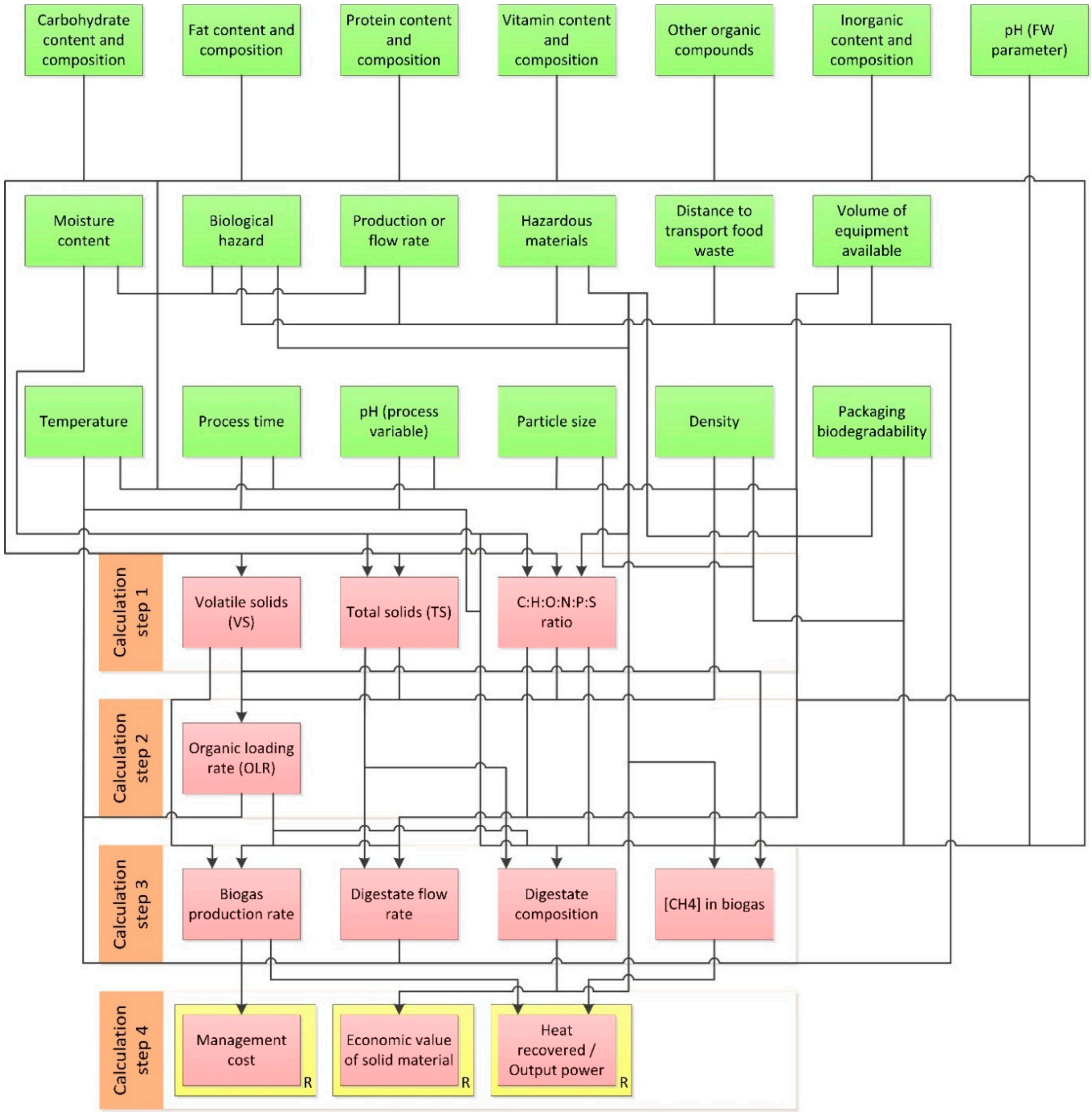

Figure 15. Information flow diagram for filter waste.

4.3. Discussion and Conclusions of the Case Study

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, 19 known attributes were shown to be needed to assess 8 unknown attributes, and these 27 attributes were identified to be needed 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. 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). The identification of additional attributes for the FWMMP is proposed as further work. In summary, the information flow diagram informs of the most efficient way to calculate unknown attributes from the known attributes within the FWMMP. If the known/unknown and required/non-required attributes change, the methodology to assess information flows must be applied again. The FWMMP, therefore, is a useful procedure that Molson Coors can use to get a better understanding of the data needed to model alternative solutions for their FWM and how to use these data to design and implement alternative FWMSs.

5. Concluding Discussion

This paper presents a standardised methodology, namely the FWMMP, to identify and assess sustainable solutions for FWM. This methodology 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 FWM decisions.

The FWMMP has been used to classify data needed to model FWM into different categories:

- FWs
- FWMSs
- food manufacturing businesses
- performance of FWM processes
- sustainability implications of FWM

Analysis of the aforementioned categories enabled the identification and classification of qualitative and quantitative attributes needed to model various FWM scenarios. Each attribute identified was independently assessed and its inclusion into the FWMMP was decided based upon its relevance to model FWM systems alongside their previous use in published research or legislation. The identification of the attributes was undertaken with the aim of providing a determinative and practical FWMMP.

The lists of attributes obtained were intended to provide enough detail to model FWM scenarios in detail. Following the aforementioned procedure, 175 attributes were identified as relevant for FWM and subsequently categorised. It is acknowledged that additional attributes may be needed in some circumstances and therefore the FWMMP is flexible: the user can add and remove attributes to adapt them to a specific scenario.

Once all FWM attributes have been identified, an analysis was undertaken to determine relationships between them on a pairwise basis. This is used to identify dependencies between attributes in order to model FWM scenarios. Results of this analysis were presented as matrices linking attributes in columns and rows. Lists of dependencies were developed from the matrices to determine which attribute from the pair depend on the other attribute. The lists of dependencies were used to draw dependencies flowcharts, which enabled the identification of dependencies between all attributes relevant to each FWMS considered.

Due to the complexity of the dependencies flowcharts, a methodology was developed to assist their use. The methodology allows the identification of the attributes required to assess the value of an unknown attribute, whether this unknown attribute depends on other unknown attributes, and which is the sequence of attributes needed until the list of attributes needed is fully known. The process provides the shortest succession of calculation steps required to assess the unknown attribute.

The applicability of the FWMMP was tested via a case study. Waste beer and filter waste from Molson Coors were analysed to support an estimation of the outputs and implications of alternative FWMSs. A combination of known/unknown and required/non-required attributes was used to generate information flow diagrams for both FW types. Consequently, all calculation steps necessary to calculate results generated from the proposed FWMSs were identified.

In conclusion, the main contribution of this paper is twofold:

1. 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. As opposed to most existing assessment methodologies, the FWMMP considers implications for the three pillars of sustainability: environmental, economic and social impacts, and benefits.

2. 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 and to a greater level of detail.

The FWMMP was not designed to compete with existing environmental assessment methodologies such as LCA, and/or socio-economic methodologies, but rather to complement their use. In fact, the output generated from the use of the FWMMP may be used to support the application of LCA or other sustainability assessment methodologies. In this way, using the FWMMP would be a pre-step for any quantitative sustainability analysis of FWM. The FWMMP can support the use of such methodologies by adding additional attributes to existing databases (e.g., ecoinvent, Agri-footprint) which would make the estimation of sustainability results from FWM more precise and would also allow creating bespoke FWM models, typically by using an LCA software such as SimaPro, GaBi or EASETECH. Also, by considering new relationships between attributes in existing FWM models more accurate results can be obtained. The methodology presented in this paper, would support the mathematical modelling of relationships, facilitating the computing of models to assess environmental categories using LCA software and potentially reducing calculation times. However, this methodology is also useful for LCA calculations by hand, without LCA software, as some lay LCA practitioners still do. In this particular case, the methodology would provide a standardised step-by-step procedure.

It is expected that FWM managers and developers/practitioners of LCA and similar sustainability methodologies would benefit from the research described in this paper so they can make more informed decisions considering the potential impacts and benefits of FWM to the economy, environment and society.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/8/2445/s1, Supplementary Material—1. List of Attributes; Supplementary Material—2. Relationships Matrices; Supplementary Material—3. Dependencies List; Supplementary Material—4. Dependencies Flowcharts; Supplementary Material—5. Table of Assessment.

Author Contributions: Conceptualization, G.G.-G., E.W., and S.R.; Methodology, G.G.-G.; Formal analysis, G.G.-G.; Investigation, G.G.-G.; Writing—original draft preparation, G.G.-G.; Writing—review and editing, E.W.; Supervision, E.W. and S.R.; Project administration, E.W. and S.R.; Funding acquisition, E.W. and S.R.

Funding: This research was funded by Engineering and Physical Sciences Research Council (EPSRC) UK, grant number EP/K030957/1.

Acknowledgments: The authors thank Molson Coors for the data provided.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Chen, H.; Jiang, W.; Yang, Y.; Yang, Y.; Man, X. State of the art on food waste research: A bibliometrics study from 1997 to 2014. *J. Clean. Prod.* **2017**, *140*, 840–846. [CrossRef]
2. Griffin, M.; Sobal, J.; Lyson, T.A. An analysis of a community food waste stream. *Agric. Hum. Values* **2009**, *26*, 67–81. [CrossRef]
3. Thyberg, K.L.; Tonjes, D.J. A management framework for municipal solid waste systems and its application to food waste prevention. *Systems* **2015**, *3*, 133–151. [CrossRef]
4. Münster, M.; Ravn, H.; Hedegaard, K.; Juul, N.; Ljunggren Söderman, M. Economic and environmental optimization of waste treatment. *Waste Manag.* **2015**, *38*, 486–495. [CrossRef] [PubMed]

5. 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.* **2016**, *131*, 607–614. [CrossRef]
6. 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.* **2016**, *50*, 4513–4523. [CrossRef] [PubMed]
7. Chen, W.; Oldfield, T.; Holden, N.M. D6.1 Integrated Sustainability Assessment Framework—Including definition of the Details, Requirements and Guidelines for LCA, LCC and S-LCA Analysis. AgroCycle. 2016. Available online: http://www.agrocycle.eu/files/2017/03/D6.1.Integrated-sustainability.pdf (accessed on 25 April 2019).
8. UNEP/SETAC Life Cycle Initiative. Towards a Life Cycle Sustainability Assessment: Making Informed Choices on Products. 2011. Available online: https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Towards%20LCSA.pdf (accessed on 25 April 2019).
9. Gbededo, M.A.; Liyanage, K.; Garza-Reyes, J.A. Towards a Life Cycle Sustainability Analysis: A systematic review of approaches to sustainable manufacturing. *J. Clean. Prod.* **2018**, *184*, 1002–1015. [CrossRef]
10. Laurent, A.; Clavreul, J.; Bernstad, A.; Bakas, I.; Niero, M.; Gentil, E.; Christensen, T.H.; Hauschild, M.Z. Review of LCA studies of solid waste management systems—Part II: Methodological guidance for a better practice. *Waste Manag.* **2014**, *34*, 589–606. [CrossRef] [PubMed]
11. Garcia-Garcia, G.; Woolley, E.; Rahimifard, S. Optimising industrial food waste management. *Procedia Manuf.* **2017**, *8*, 432–439. [CrossRef]
12. Bisinella, V.; Götze, R.; Conradsen, K.; Damgaard, A.; Christensen, T.H.; Astrup, T.F. Importance of waste composition for Life Cycle Assessment of waste management solutions. *J. Clean. Prod.* **2017**, *164*, 1180–1191. [CrossRef]
13. Gentil, E.C.; Damgaard, A.; Hauschild, M.; Finnveden, G.; Eriksson, O.; Thorneloe, S.; Kaplan, P.O.; Barlaz, M.; Muller, O.; Matsui, Y.; Ii, R.; Christensen, T.H. Models for waste life cycle assessment: Review of technical assumptions. *Waste Manag.* **2010**, *30*, 2636–2648. [CrossRef] [PubMed]
14. 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.* **2015**, *36*, 12–23. [CrossRef] [PubMed]
15. Patsios, S.I.; Kontogiannopoulos, K.N.; Mitrouli, S.T.; Plakas, K.V.; Karabelas, A.J. Characterisation of Agricultural Waste Co- and by-Products; AgroCycle. 2016. Available online: http://www.agrocycle.eu/files/2017/03/D6.1.Integrated-sustainability.pdf (accessed on 25 April 2019).
16. Laurent, A.; Bakas, I.; Clavreul, J.; Bernstad, A.; Niero, M.; Gentil, E.; Hauschild, M.Z.; Christensen, T.H. Review of LCA studies of solid waste management systems—Part I: Lessons learned and perspectives. *Waste Manag.* **2014**, *34*, 573–588. [CrossRef] [PubMed]
17. Garcia-Garcia, G.; Woolley, E.; Rahimifard, S.; Colwill, J.; White, R.; Needham, L. A methodology for sustainable management of food waste. *Waste Biomass Valorization* **2017**, *8*, 2209–2227. [CrossRef]