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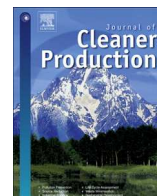
A complete decision-support infrastructure for food waste valorisation

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ABSTRACT

The quantity of energy and materials embodied in food means that wasting a third of it, which is the level of inefficiency reached according to studies in recent years, impacts negatively on living standards at whatever level they are around the world. An increased level of consciousness about the issue has stimulated initiatives to address it, leading, sensibly, to the development of decision-making systems to support proper management of the materials. Here, we present the first review and evaluation of four recently developed systems targeting food waste. These tools broadly embody a logical model which identifies and quantifies food waste flows at different scales, characterises them, identifies appropriate conversion technologies, and enables assessment of the economic, environmental and social effects of different pathway options, along with other factors to provide a final fit with the circumstances of each owner of the food waste. Our review concludes that these tools are necessary but not sufficient to lift the management of food waste from a grossly sub-optimal level to a system which would be recognised by pre-and emerging-industrial generations but with valorisations of much higher value. Specifically, we identify knowledge-based elements of a management system which would be free of specific supply chain context and therefore have much greater power to direct resources affordably for maximum economic, environmental and social value.

1. Introduction

1.1. Background

In 2017 the Drawdown project (Hawken, 2017) identified the 100 most powerful solutions to global warming, and reduction of food waste was number three. This supports the intense activity now focused on implementing this solution (Chen et al., 2017 (describing the state of the art in food waste research); European Commission, 2019 (the European Food Loss & Food Waste Platform)). At the same time, there is the recognition that some food waste will always be created: in addition to some edible parts of food being discarded and therefore not consumed by people due to a number of reasons, inedible materials, which will become a waste stream, are often associated with food products. These inedible materials, common in the food processing and manufacturing stage of the supply chain, have been generally classified as unavoidable waste. The concept of 'food waste' (FW) encompasses both edible and inedible materials, and can be defined as food materials originally intended to be used to feed humans and not ultimately sold for human consumption by the food business under study, and the inedible parts of food (Garcia-Garcia et al., 2016).

In Europe, research and development activity on how best to maintain or even increase the value of this material in economic and environmental terms has now moved to a consolidating stage; information on the quantities, locations and characterisation of FW, conversion technologies and potential target products is being assembled and frameworks and tools are being produced to support decision-making. Such tools are often not independently validated, and little used once project funding ends. They are generally not commercialised as software for which people will

pay, or adopted into international standards. This paper sets out systematically to evaluate these aids and to present a framework for the next stage of their development. If so developed, they would carry more weight and more likely to become incorporated into practical decision-making in the food supply chain. We are not aware of any other such evaluation.

This activity is in line with the objectives of the EU's Bioeconomy Strategy. The 2017 review of this Strategy concluded that (their emphasis):

> "**Better monitoring and assessment frameworks are needed to assess progress**. As sustainability in terms of production and consumption is core to the bioeconomy strategy, better understanding is necessary of the prospective development of biomass supply and demand, to ensure that the bioeconomy operates within the limits of the biosphere, while providing optimum social and economic gains."

1.2. FW valorisation decision-support guidance and tools: descriptions

A thorough review of the literature concerning methodologies for selecting the best FW valorisation technique was conducted by Stone et al. (2019). This led to the development of the SWaVI (Sustainable Waste Valorisation Identifier) pragmatic framework, which was described in detail in that paper.

A parallel development has been the output of three major publicly funded initiatives, which have been aimed at supporting practical improvements to FW management. This sub-section summarises the structure and content of the four guidelines/tools.

1.2.1. Resource efficient food and dRink for the entire supply cHain (REFRESH)

REFRESH (2015–2019) is an EU research project that involves 26 partners from 12 European countries and China. It follows successful previous EU FW projects such as FUSIONS (Food Use for Social Innovation by Optimising Waste Prevention Strategies). REFRESH is addressing all issues associated with food waste, mainly at the household and retail end, but also industrial valorisation. Its stated overarching aim is "to "develop the blueprint for a pan-European Framework for Action", in order to support "better decision-making by industry and individual consumers" and "to develop, evaluate, and ensure the spread of social, technological, and organisational insights and practices related to food waste" (REFRESH, 2019). Its remit includes the design and development of technological innovations to improve valorisation of food waste.

1.2.1.1. Relevant outputs. Outputs to date relevant to industrial food waste valorisation are:

- Identification of food waste streams with high potential for valorisation (Sweet et al., 2016), along with analysis of the status quo in food waste management and valorisation (Metcalfe et al., 2017) and consumer perception on the final use for human or animal feeding of such valorised products (Rahmani and Gil, 2018).
- Reports on simplifying Life-Cycle Assessment (LCA) and Life-Cycle Costing (LCC) methodologies to enable owners of FW or their stakeholders to generate an initial view on the best processing options from environmental and cost perspectives (De Menna et al., 2016 (LCC); Unger et al., 2016 (methodology for evaluating environmental sustainability); Davis et al., 2017 (LCA and LCC); Östergren et al., 2018 (LCA and LCC)).
- A spreadsheet tool, 'FORKLIFT' (FOod side flow Recovery LIFe cycle Tool), which embodies the LCA & LCC approach, as well as

containing a database of FW composition. (This uses the long-standing UK reference McCance & Widdowson's.) At the time of writing, 'FORKLIFT' was not available for use or analysis.
- A short online tool to enable custodians of surplus food to determine if it can be used to feed farm animals.

REFRESH results have provided these frameworks for analysis, together with data on a few specific FW feedstocks, conversion pathways and products to illustrate the application of the frameworks.

1.2.2. AgroCycle

AgroCycle is a Horizon 2020 research and innovation project that addresses the recycling and valorisation of waste from the agri-food sector. It comprises 26 partners, including partners from eight EU countries, two partners from mainland China, and one from Hong Kong. AgroCycle aims to support the implementation of "sustainable waste valorisation pathways addressing the European policy target of reducing food waste by 50% by 2030, as well contributing to the wave of change that is occurring in China in relation to sustainability" (Agrocycle, 2019a).

1.2.2.1. Relevant outputs. The most relevant outputs of AgroCycle (Agrocycle, 2019b) in the context of industrial food waste valorisation are:

- Waste flow data for the different wastes arising from meat/fish, fruit, cereals and vegetables along the whole value chain in each EU28 country, including analysis of their relevant legislation, supply chains and logistics involved in food waste valorisation.
- Some current and potential extractions/conversions and their products and applications, using published data and the patent record.
- The physicochemical composition of two types of by-product and waste arising from each of 26 commodities, related to energy, fodder, fertiliser, wastewater and bioactive compounds.
- A Sustainability Assessment Framework for the sustainability performance of food waste and by-product valorisation, covering environmental, economic and social aspects.

Additionally, AgroCycle also created reports to support data collection for these aspects of the framework.

1.2.3. WRAP

The Waste and Resources Action Programme (WRAP) is a government-backed organisation that aims to implement a more resource efficiency economy in the UK. WRAP has led a large number of initiatives to reduce food waste and provided most quantified estimates of UK food waste flows.

1.2.3.1. Relevant outputs. In the UK, WRAP has produced several reports and tools under the banner 'Getting more value from waste and surplus food & drink.' These include:

- The Courtauld Commitment, a voluntary agreement aimed at improving resource efficiency and reducing waste within the UK grocery sector (WRAP, 2018a).
- Estimated quantities of food waste arising in the UK supply chain (WRAP, 2018b).
- A 'Business Case' tool (an Excel workbook, WRAP, 2017) which assembles all the factors influencing FW valorisation into a logical sequence, joining them up with appropriate formulae to enable quantification and comparison of different processing and output options.

- Information and data on conversions of the FW categories, referenced by the Business Case tool, are available from WRAP in separate documents.

1.2.4. SWaVI (Sustainable Waste Valorisation Identifier)

SWaVI was developed by Stone et al. (2019a) as part of the UK project "Whole systems understanding of unavoidable food supply chain wastes for re-nutrition." It takes a slightly different approach to the previously reviewed works in the sense that it aims to help companies identify the best FW valorisation option for their bespoke situation, rather than trying to identify the outright most sustainable valorisation option for a given FW stream. It achieves this through five stages including an analysis of the characteristic and composition of FW to hand, stakeholder assessment, followed by selection of the best aligned valorisation options, selection of the most suitable indicators (including environmental, economic, social, technological and brand fit indicators) and finally ranking of the valorisation options depending on measurements from each of these indicators. A strength of this approach is that it considers a broad range of empirical measurements, which are then weighted and normalised to make an easy to understand and holistic recommendation for managers. However, a drawback is that the level of depth recorded for each indicator, for example, environmental impact, is less than could be achieved via a full LCA and so the framework is best suited for initial identification of optimal valorisation routes for a given company. The SWaVI tool relies on users then applying full LCA/LCC to guide implementation of whichever valorisation route they ultimately choose. Currently the SWaVI principles have been published and demonstrated in a step-by-step case study, however, this has not currently been released in the form of a publicly accessible tool.

1.2.4.1. Relevant outputs

- A publication containing full guidelines on the principles of the SWaVI framework and a step-by step guide to its implementation with a case study illustration (Stone et al., 2019a).

- A further publication considering systemic barriers and potential supply chain level ramifications that might be faced if a company were to alter their food waste valorisation strategy based upon recommendations from the SWaVI tool (Stone et al., 2019b)

1.3. Structure of the paper

Having set out the state of the art in decision-making support for FW valorisation, we can now proceed to assessment. Section 2 of this paper is a partial review and critique of the above four guidelines and tools now becoming available to support effective selection of FW valorisation options. The conclusions lead to identification of additional features which are insufficiently covered in the tools or which they do not provide. A detailed description of these features, presented in section 3, constitutes an expanded and, it is suggested, a more powerful decision-making infrastructure for the valorisation of FW. Section 4 completes the analysis by proposing the key areas for research and development in progressing toward construction and use of the proposed decision-making infrastructure.

2. FW valorisation decision-support guidance and tools: assessment

Section 1 has reviewed various approaches to guide the valorisation of FW, generated by Refresh, Agrocycle and WRAP as well as

the SWaVI framework from the academic literature. All four sources of guidance offer a range of outputs with some underlying similarities in approach, but also a range of differences. The next step is therefore to assess strengths and weaknesses of each of the contributions, through the lens of a generic model underpinning each of the four approaches which we have identified. This subsequently enables identification of the knowledge gaps which need to be addressed in order to enable the valorisation of food waste to be performed in a more efficient and synchronised manner at a national scale.

2.1. Existing tools − underlying similarities

The approaches applied in all four initiatives have a solid general logic:

1. Identify material flows by type, quantity, location and time (at site and/or country level).
2. Characterise the composition of the materials.
3. Identify suitable valorisation products and technologies.
4. Apply economic, environmental and social values to the data in steps 1 & 3.

WRAP and SWaVI have an additional step involving a scoring of the options arising in order to rank them and then make a final judgement on how the FW should be processed. In the WRAP tool, this scoring is subjective, based upon the user's own perspective and weighting using a Likert scoring system. In the SWaVI framework, data inputs are objective, using a variety of measured values such as costs and environmental emissions which are then normalised for comparison.

The underlying logic (steps 1−4 above) could be integrated within the following relationships:

$$\text{Optimum Processing Action } = f\left[\frac{M_Q}{M_{TYP \times Q}} \times \rho \times \tau\right] \qquad (1)$$

where M = the FW arising, characterised by composition; Q = quantity; TYP = the type of FW arising; ρ = the economic, environmental and social assessment of the products deliverable from valorisation of the FW; and τ = the same assessment of the technologies which could deliver the products. The 'location' element of step 1 is a contributing factor to ρ and the 'time' element is a contributing factor to Q.

2.1.1. Existing tools − strengths, weaknesses and knowledge gaps

The underlying principle of the reviewed guidelines and tools is that a combination of waste composition, quantities, technological enablers and sustainability performance can inform the selection of a valorisation strategy for each waste stream. Their effectiveness and shortcomings can be assessed using the Ideal Final Result (IFR) concept and the 9-windows tool from the Theory of Inventive Problem Solving (TRIZ) stable of engineering and business innovation tools (Mann, 2007). This is designed to rigorously guide arrival at the most optimal solution to a challenge, regardless of the industry applied to, thus acting as an analytical lens through which to compare the functionality of each of the reviewed food waste valorisation guidelines and tools. In this way, Fig. 1 shows the components of an ideal system for FW valorisation, integrated by system level and time. System subfeatures for each valorisation step combine to characterise each step and inform decisions, whilst the universe of knowledge at the superfeature level is also drawn upon. Perfect knowledge of past and future variables is used in the present, and perfect control can be exercised over all features.

This shows up the following gaps under each of the steps of the above generic model:
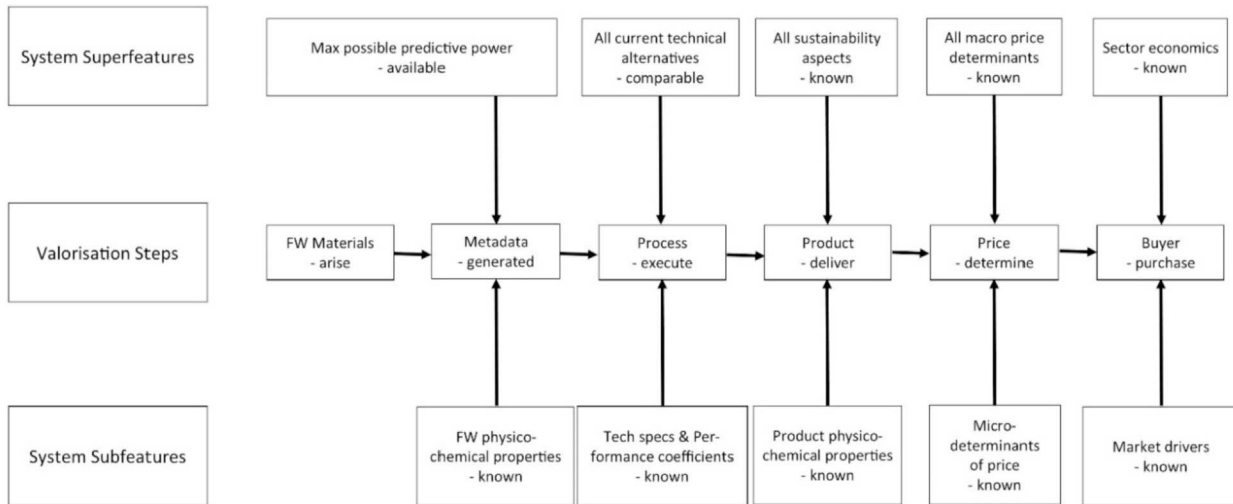
Fig. 1. Components of an Ideal Final Result system for FW valorisation by system level and time.

- Identify material flows by type, quantity, location and time (at site and/or country level).

This is well covered by the four tools. Whilst WRAP allows an estimated approach to quantities as a way of enabling prioritisation of materials flows with low effort and cost, the predictive power built in to the other tools is unclear.

- Characterise the composition of the by-product/waste materials (Subfeatures, first box).

REFRESH, AgroCycle and WRAP all characterise in standalone documents the starting materials in terms of their elemental content and mineral and nutritional compounds, and SWaVI contains provision for incorporating this information. None of the tools characterise the FW arising in terms of physico-chemical properties, such as chemical groups (which have particular properties such as polarity), mechanical and electrical properties. Section 3.2.3 describes the value of this. None of the tools contain embedded databases of materials information for inputting to the tool.

- Identify suitable valorisation products and technologies.

The guidance and tools enable valorisation products to be identified from the starting material based on previous specific research findings. None of the tools enable the valorisation products to be identified (Subfeatures, third box) from the physico-chemical properties of the starting material (Subfeatures, first box).

None of the tools enable conversion technologies to be characterised in terms of common technical specifications and performance coefficients (Subfeatures, second box), nor, as a consequence, comparison at the super-system level for the same conversion (Superfeatures, second box).

- Apply economic, environmental and social (EES) values to the data in steps 1 & 3 (Superfeatures, third box).

WRAP attaches economic values while SWaVI attaches EES values. SWaVI therefore allows larger system implications to be taken into account, such as the environmental effects of displacing a current use (e.g. for animal feed), which could involve feed material with a higher environmental impact, such as imported soya. Importantly, this will also enable unintended consequences to be

spotted in advance.

WRAP relies on the user scoring each criterion using a Likert scale to generate traffic light categorisations of materials in terms of quantity, composition and disposal cost. WRAP then has an aide memoire in the form of questions about other issues such as flow variation, treatment facilities and storage, both as currently known and possible future options or potential, which are assessed by the executive user in their own way. SWaVI instead assigns empirical values to each of the criteria, which are weighted and normalised to facilitate comparison of the different scales. The WRAP tool is very simple to use and collect data for, but this approach is very much dependent on the responses of the user being objective and unbiased which obviously may not always be the case. SWaVI attempts to circumvent this by relying on measured values yet this can be more time consuming for the user and is vulnerable to distortion if weighting is not performed accurately.

The AgroCycle EES data comprises a full LCA of one valorisation process for each of four by-product/wastes categories (animal manure/slurry through micro anaerobic digestion); fertiliser from rice by-products; fruit processing wastewater; bioplastic from potato pulp). It illustrates the use of the AgroCycle Protocol for carrying out such assessments. There does not appear to be a tool with which this detailed information can be used in the field.

The REFRESH guidance on LCA recommends evaluation against the four impact categories most used in food LCAs. This is suited to professional users. The practical tool, FORKLIFT, enables users to estimate only greenhouse gas (GHG) emissions and the total costs (along the supply chain) per tonne of FW to be valorised into target products. The results, though only indicative, are compared to average footprints of similar products with the same function.

- Knowledge of effective systems

In the IFR scenario, actors in the system have full knowledge of how systems work effectively — the underlying dynamics. A particular aspect of systems is how they develop and survive or flourish by adapting to challenge or opportunity — that is, how they innovate. WRAP, AgroCycle and SWaVI do not include this knowledge to inform successful implementation of food by-product/ waste valorisation pathways. REFRESH has established a 'Community of Experts' website, described as a "knowledge sharing platform to find and share information about proven solutions and innovative new approaches to … divert food and scraps to the

highest beneficial use." This is a bottom-up accumulation of knowledge about innovation.

- Control

All the tools discussed in this section are directed towards people with executive authority at individual sites, whether creating or receiving the by-product/waste material. The designs rely heavily on the FW owner or prospective processor or other relevant executive entering all the relevant data for their sites and materials into the tool, which requires significant effort and time. This weakness is addressed in section 3.4.

2.2. Assessment conclusion

We have used the Ideal Final Result concept to analyse where the comprehensive initiatives aimed at tackling FW may fall short of the ideal approach. This showed the following gaps and shortfalls:

- No characterisation of FW materials in terms of physico-chemical properties. The data gathered is bottom-up, from a large number of studies at lab and pilot scale.
- As a result, potential products of valorisation cannot be identified from the physico-chemical properties of the starting material.
- Reference data is in standalone documents, rather than embedded into an electronic tool, a critical feature if a tool is to be practically useable.
- Conversion technologies are not characterised in terms of common technical specifications, so it is also difficult to compare their performance for the same feedstock to product conversion.
- SWaVI and AgroCycle have guidelines for incorporating life-cycle implications of choices into decisions, yet these have not been standardised into a publicly available tool. They are also complex for the non-professional user. REFRESH also has guidelines, again more suited for professionals. It has developed the 'FORKLIFT' tool, but the only environmental measure is GHG emissions, and it does not appear to be available.
- None of the tools includes bigger system, cross-disciplinary knowledge, particularly with respect to innovation dynamics, which are important for understanding how innovation can be effectively adopted in the marketplace.
- All the tools place a large burden on many individual decision-makers. There is not (yet) an effective mechanism for co-ordination of decision-making, effort and investment.

In summary, it can be seen that a large amount of knowledge has been accumulated on how technically to valorise food by-products/waste, along with understandings of the different criteria which would need to be measured to assess the business and sustainability case for each. However, arguably none of the reviewed approaches have been able to form a single tool with the power to galvanise stakeholders.

Part of the challenge stems from the fact that the knowledge accumulated has mainly been derived from and is directed towards linear processing - one or two types of material from one foodstuff extracting single products. Valorisation of the remaining parts of the FW has not received attention as part of a whole, integrated system, often referred to as the biorefinery concept, and so the full value of the FW cannot be realised with the current design of the tools (Moncada et al., 2016). In line with this, the initiatives do not contain much chemical and biological engineering content. Chemical and biological engineering are the foundation domains

for optimum industrial valorisation of food by-products/waste.

There are a number of techniques which could facilitate such a biorefinery approach to food waste valorisation and in doing so aid uptake and synchronisation of food waste valorisation at a national scale. These are now discussed at length.

3. Tool improvements

It is clear from the four different tools reviewed that, whilst each have their own merits and drawbacks, all have been constructed in isolation. To address the gaps summarised in section 2, synthesis is necessary to bring together the strengths and weaknesses of the aforementioned models and present possible improvements with the aim of stimulating further research. To our knowledge, this article is the first to attempt such a synthesis of food waste valorisation tool best practice. .

3.1. Overview

Fig. 2 is a representation of the FW value chain, and its dynamics arising from both the current initiatives (including the sub-optimal features identified above) and the potential improved dynamics proposed in this paper.

The overall picture is that the knowledge necessary to fully valorise FW within any country or regional boundary is insufficient and/or insufficiently related. Insufficiency of any resource, including intangibles such as knowledge, equals scarcity, which results in upward pressure on prices and costs.

The next evolutionary steps should be: integration of disparate existing knowledge about FW feedstocks, conversion technologies, possible products, and the associated costs and revenues associated with these; segmentation of this knowledge and associated other resources into manageable units which can establish and grow; and co-ordination of both integration and segmentation along with system resources so that they are all leveraged, in the true engineering sense, to lower the work function needed for effective growth of FW valorisation activity. The rest of this section sets out how integration, segmentation and co-ordination can be achieved, drawing on various approaches in other industries and disciplines as well as introducing new ideas.

3.2. Integration

The integration of disparate knowledge is often prevented by insufficiently structured knowledge. The starting point for analysis is to appreciate the two kinds of paradigm associated with the valorisation of bio-resources, shown in Fig. 3.

In general FW has much less lignocellulosic content than other biomass feedstocks, and most of the research on FW valorisation has focused on molecules present in the material which are also the target products. With lignocellulosic biomass, the design paradigm is to break down the polymers in order to then recombine them into target molecules. A minority of the lignocellulosic material comprises target molecules which are simply to be extracted.

3.2.1. FW knowledge

There are two challenges associated with structuring knowledge about FW valorisation. The first is to understand the molecular composition of FW by category and individually, and the second is to understand the optimum processing pathway. The latter is addressed in section 3.2.4.

As observed in the Review, research to date on FW composition has laid a foundation of empirical knowledge about individual foods and extractions of target molecules and substances. For example, the 'information and data' on conversions of the FW
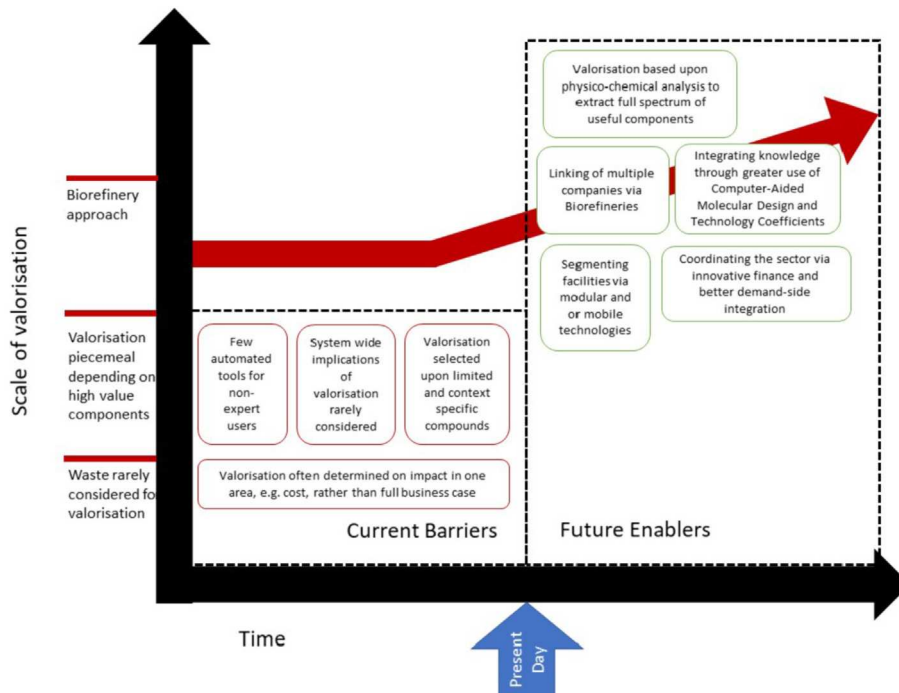
Fig. 2. Proposed Elements of the pathway for improvement of FW Valorisation Decision-Support Tools.

categories referenced by WRAP's Business Case Tool is an assembly of processes and outputs drawn from the academic and other literature. Some of these processes/outputs do not change or extract the chemistry of the material (e.g. use of breadcrumbs to make beer), and for those which do, they are standalone processes with single outputs (e.g. lactic acid production from bread crust fermented with yeast).

Whilst a useful library, this deterministic approach is a time-consuming and expensive way to generate knowledge. It also cannot accommodate all the variations in composition which exist (e.g. significant differences in the galacturonic acid content of mango peel pectins, Geerkens et al., 2015), the many compounds which could be extracted, combinations of those compounds, and most importantly when in the cascade of valorisation steps the valorisation should be completed. The next step is to translate the researched information to a higher level of abstraction, together with models based on thermodynamics and other theoretical foundations, to create a more powerful tool for understanding the functional value of the feedstock material. This also opens up the potential for novel combinations or additions to the target molecules for extraction, and novelty or added functionality to outputs. It also informs the design of processing pathways.
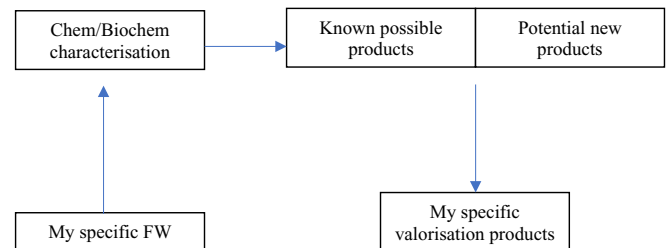
Fig. 4. Simple schematic of information conversion using an ontology.

3.2.2. Lignocellulosic biomass knowledge

The above approach is more important for lignocellulosic material because it contains many fewer ready-made molecules for extraction.

3.2.3. Higher-level knowledge

To move to a more powerful valorisation design tool, the categories of feedstock, whether FW, lignocellulosic biomass, or both, and in many cases their sub-categories, need to be characterised in terms of the chemical groups, molecular structures and the atomic relationships they contain. Possible molecular conversions can then

Fig. 3. Simple schematic comparing two biomass valorisation pathways.

Table 1
Example application of the Universal Recovery Strategy for the Characterisation stage (expanded from Galanakis, 2015).

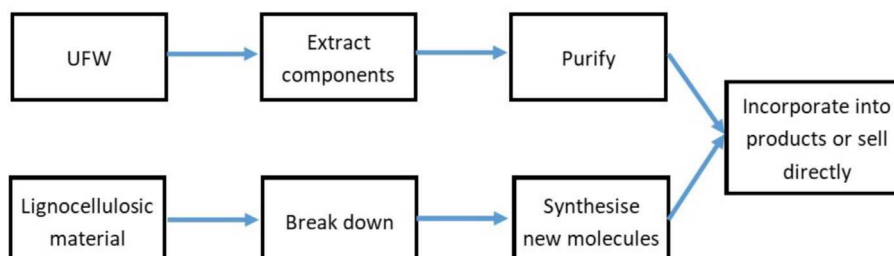| Level		Group	Characterisation
1	Macroscopic	Peel, pulp, seed	Type, phase
2	Microstructure	Crystalline, amorphous, polymeric, etc.	Viscosity, fibre length, inter-molecular bonding
3	Compounds	Phenols, sugars, dietary fibres, etc.	Chemical structure
4	Target macromolecules	Hemicellulose Pectin	Molecular weight, intermolecular polarity, charge, isoelectric point
	Target micromolecules	Polyphenols	Structure, molecular weight, # aromatic rings, hydroxyl, carboxyl & methylation groups
5	Microbial & enzyme load	e.g. pectin methyl esterase, polygalacturonase	Identification of load
6	Functional properties of ultimate target compounds	Gelling	Pectin de-esterification and solubilisation

be applied, along with suitable processing technologies, in order to define the most feasible process and intermediate/final products. This ontological approach follows and elaborates on that of the seminal paper which first crystallised the biorefinery concept (US Department of Energy, 2004). A particular advantage is that it avoids reliance only on knowledge of specific pathways/products previously researched, but gives predictive power and enables innovation in new pathways/conversions. Fig. 4 is a simple schematic of the concept.

The much-studied extraction of pectin from fruit side-streams could be used as an example of FW valorisation. Pectin is a heteropolysaccharide mostly formed of chains of galacturonic acid. Its exact composition differs by feedstock, but a major component is L-arabinose. The structure of L-arabinose is complementary to that of limonene, also found in fruit FW. If the two were combined, the polarity of the hydroxyl group on the limonene would increase, potentially making it a strong detergent.

There are already tools which embody this approach, which are described in the following sub-sections.

3.2.3.1. Universal Recovery Strategy. Galanakis (2015, 2018) advocated a 'Universal Recovery Strategy' for food waste (in which 'recovery' meant both recovery and characterisation), followed by the more detailed '5 stage Universal Recovery Process' (in which 'recovery' meant what many others would call 'valorisation' or 'processing').

The Strategy involves identifying FW and characterising it on six levels:

1. Macroscopic
2. Microstructure
3. Grouping of compounds
4. Determination of target macromolecules
5. Microbial and enzyme load
6. Functional properties of target compounds.

This information then informs the Process, in which processing technologies are identified according to each of five treatment steps (Macroscopic Pretreatment; Macro- and Micro-Molecules Separation; Extraction; Isolation & Purification; Product Formation). The treatment steps use either incumbent or emerging technology pathways.

The Universal Recovery Strategy and Process provide a new level of order for accessing the large body of relevant chemical and biochemical engineering knowledge. They allow enhancements in process and product efficiency and quality respectively by revealing the atomic and molecular relationships in the feedstock which influence the formation of product molecules. The most important feedstock parameters at the macromolecular level are listed as molecular weight, intermolecular polarity, charge and isoelectric point,

whilst for micromolecules they are molecular weight and the number of aromatic rings, hydroxyl, carboxylic and methylation groups. The microscopic level (e.g. micromolecular "cell walls, starch granules, water and oil droplets, fat crystals and gas bubbles") influences the macroscopic, particularly in the formation of supporting and interleaved structures such as macromolecular "colloidal dispersions, emulsions, amorphous and crystalline phases, gels."

Values for these parameters can be acquired from existing databases or using suitable spectrophotometry methods. These then enable selection of target products and the optimum processing technology or technologies.

Use of the Universal Recovery Strategy for characterisation can be illustrated with apple pomace, as shown in Table 1:

It appears that this approach has not yet been implemented in the design or operations process of a physical plant, nor with non-solvent technologies, so this is a research opportunity.

3.2.3.2. Computer-aided molecular design. The Galanakis framework makes partial use of computer-aided molecular design (CAMD). CAMD is a well-known approach to the design of chemical engineering pathways to achieve target functions from a pool of potential feedstock molecules.

The CAMD knowledge base is molecular structure and its relationship to properties which provide functions. Feedstock and product molecules are characterised in terms of Quantitative (or Quantified) Structure-Property Relationships (QSPR). Molecular structure can be broken down into a hierarchy of sub-structures, each of which contribute to aspects of the molecule's properties. CAMD is a semi-empirical approach because its knowledge is derived from a combination of experimental results and more generalised relationships based on thermodynamics and other theoretical foundations.

The power of CAMD is that, like the Galanakis approach, it enables the whole universe of potential conversions of feedstock molecules to be seen and evaluated.

CAMD uses three types of QSPR. Probably the most used is Group Contribution which identifies a molecule's properties by the number of sub-structures it contains. For example, butanol, with the structure shown in Fig. 5, is characterised in terms of the groups 1 x CH_3, 3 x CH_2, 1 x OH).

The contribution of each group to a target property is then assessed as a simple multiplication of the number of each group by a coefficient for the contribution of each group to the target property. The coefficients are derived from large datasets relating to the target property across many different molecules.

The other two relational or predictive methods used in CAMD are Topological Indices (TIs) and Signature Descriptors (SDs). Both of these plot geometrical and — optionally — bonding and electronic features of molecular sub-structures (atoms and bonds) onto 2D and 3D graphs, and attach values to each feature. Features and their
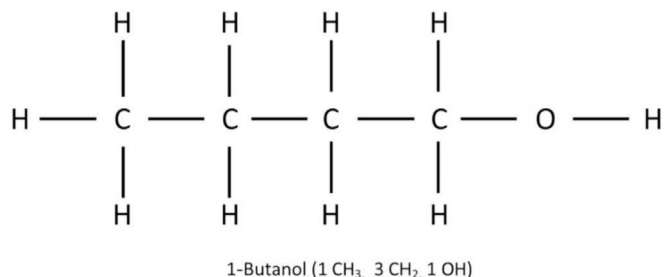
Fig. 5. Example of group contribution molecular structural representation.

combinations are then related through regression coefficients from many observations (training data) to properties of the molecule, such as those listed below, showing a small sample of those which have been elucidated using TI and SD methods.

- Anti-inflammatory activity
- Aqueous solubility
- Biodegradability
- Boiling & melting points
- Heat capacity
- Refractive index
- Vapour pressure
- Viscosity
- Water-air partition coefficient

This deciphering of structure in terms of properties enables molecules with target properties to be structured, and a conversion pathway between the feedstock molecule and the target can be designed, taking into account the property values enumerated.

CAMD has been mostly used to design single molecule products, and much less for mixtures, where the computational requirements multiply.

QSPR is also the basis of QSAR (Quantitative Structure-Activity Relationship), used for identifying substitutes for molecules with toxic effects, and this environmental dimension can also therefore be incorporated into CAMD modelling.

CAMD has not penetrated far into the design of biorefineries or single product valorisations. In the past decade, a small number of researchers have used CAMD and other systematic screening tools for designing processing pathways in biorefineries, including those shown in Table 2.

A wide review of these is given by Ng et al. (2015), and a larger set used with biorefining optimisation is given by Yuan et al. (2013). Ng et al. used CAMD to design integrated pathways for biorefining

products which required mixtures of inputs rather than single molecules. They exemplified this for the design of fuel additives from palm oil biomass. Previously, CAMD had been almost always been used for chemical engineering products, some of which were transferable to biorefineries, such as identification of optimal solvents for fermentation to extract ethanol from glucose (Wang and Achenie, 2002) and acetic acid from a wastewater stream (Gebreslassie and Diwekar, 2015), and design of ionic liquids (Karunanithi and Mehrkesh, 2013).

An excellent description of CAMD and its application can be found in Austin et al. (2016).

3.2.3.3. CAMD software. Ultimately, the outputs of the research community need to be converted into practical tools, in particular widely used software, if their intended value is to be realised. There are two types of such software:

a) Library-based

Established packages such as Molinspiration Cheminformatics (Molinspiration Cheminformatics, 2018) draw on a library of empirical data and previous modelling to inform user manipulation of molecular features and processing.

b) Intelligent

Intelligent packages also draw on libraries, but in addition they use algorithms to identify patterns and relationships in that data, so that they are able to predict a conversion pathway and product molecules with user-specified properties from feedstock molecules. This intelligence grows as they are trained on ever-increasing data sets and their algorithms are refined.

UNIFAC (Universal Functional-group Activity Coefficients) (UNIFAC Consortium, 2018) partly has this capability, and is incorporated, with limitations, into the main commercial process engineering design packages. IBM's Research division has recently released an intelligent, free cloud-based product called *RXN for Chemistry* (IBM Corp, 2019). Users characterise their starting molecules in structural terms via a purpose-designed interface, then add reactants, reagents and process conditions from preconfigured libraries or their own sources. The algorithms are trained on two text-mined patent sets comprising 500k and 350k patents (it is not stated whether or not these were granted). From these, structures are extracted and represented as SMILES sequences (text-based representations of chemical structures). The algorithms have been validated with empirical data, achieving [88%] accuracy, a ~10%

Table 2
Methods used for design of processing pathways in biorefineries.

Insight-based Approaches	Description	Example Reference
Pinch analysis	Identifies the minimum temperature gradient for heat exchange in a process, to enable design to deliver specified performance in all process conditions.	Martinez-Hernandez et al. (2013)
C−H−O ternary diagrams	Determines stochiometric quantities of reactants to convert organic substances to target molecules.	Tay et al. (2011)
Process graph method (P-Graph)	By abstract representation of materials and operations in a process, enables the universe of possible conversions of input material to be refined down to those which meet criteria, such as lowest cost.	Halasz et al. (2005)
Mathematical Optimisation Approaches		
Linear & non-linear programming	Common methods of selecting the combinations of linear or non-linear constrained variables which will achieve a targeted outcome (objective function).	Gebreslassie et al. (2013)
Disjunctive programming	Eliminates consideration of discrete process elements and variables to enable simpler computation.	Ponce-Ortega et al. (2012)
Fuzzy optimisation	Feedstock, process and product characteristics are assigned non-integer values (between 0 and 1), enabling tradeoffs between values to reveal an optimal combination for the achievement of target outcomes.	Andiappan et al. (2015)
Superstructure-based	A biorefinery superstructure, by reference to target product functions, comprises: optimal mixtures of feedstocks and process agents; optimal conversion pathways.	Ng et al. (2015)

improvement on predecessor competing modelling.

RXN for Chemistry continues to learn through user input and iteration. Importantly, the algorithms do not embody or require chemistry knowledge, being the equivalent of machine translation algorithms. IBM's Chef Watson (Varshney et al., 2019) provides a precedent for the application of *RXN* to biorefining; Watson produced some attractive unique food combinations at molecular level, which had not been spotted by humans.

A clear possible next step is to incorporate CAMD into SWaVI. The opportunity is there for stakeholders interested in solving the problem of unavoidable food waste to develop suitable user-friendly packages which have this enhanced power.

3.2.4. Technology coefficients

Along with the characterisation of feedstock and target product molecules just described, process technologies are a critical consideration for the economic and environmental viability of FW valorisation.

System design in process engineering is supported by process software packages such as Aspen and ProSim. These have extensive libraries of data for particular processes and calculation algorithms for thermodynamics and other fundamental aspects of a system.

These software tools have not yet developed to the ontological level as described for materials properties above. This includes the particular technical means to achieve transformations. Data is embedded for incumbent technologies, but has not been represented at an abstract level to enable flexible identification of more radically efficient technologies such as those referenced in Galanakis's Universal Recovery Process (Galanakis, 2015).

Bonatsos et al. (2016) moved towards this in modelling to select the optimum microbial fermentations of molasses, sucrose and glycerol using some coefficients, such as the linear relationship between fixed investment cost and reactor volume to determine values for capital expenditure, and the inverse relationship between yield coefficient and cost of raw materials as a proportion of manufacturing (refining) costs. However, they still use metrics from a literature search to identify and characterise 25 possible microbial processes. Moncada B, Aristizábal M, & Cardona A, (2016) used published microbe-specific kinetic models as the key reference data for evaluating different microbial conversions of sugarcane bagasse for the same products. Neither of these compare technologies from different technical domains. Rivas, Castro-Hernández, Villanueva Perales et al. (2018) have published perhaps the simplest and most flexible model to date using process intensification to compare any factor - e.g. technical, economic, environmental, safety - which may influence an objective to be achieved. This involves a simple calculation of 'Intensification Factor' (IF):

$$IF = \left(\frac{Fb}{Fa}\right)^d \tag{2}$$

where *Fb* is the value for a factor *F* before a technology change (the status quo), *Fa* is the value after the technology change, and *d* is an exponent which acts as a weighting. *F* can comprise any type of value for a domain, so for the technology domain it could comprise variables such as pressure, temperature and flow rate. In their model addressing the same type of problem, Andiappan et al. (2015) used Total Heat of Reaction as the energy efficiency measure, concluding that it needed to be more nuanced. The values of *d* for various calculations of *IF* are set to unity if values are not known or cannot be estimated, otherwise they are drawn from empirical observations. In four cases, the researchers demonstrated the value of this formulation in supporting system design and innovation, in enabling non-specialists to use it, and in communicating to non-specialist stakeholders and decision-makers such as the Finance Director. However, the approach still relies on empirical data to distinguish between technologies rather than indices of performance, as advocated here.

A simple example of such an index to compare technologies would be energy efficiency (EE). Based on a model by Seow et al. (2016), this would allocate technologies into EE bands for (a) conversion from energy source to the process equipment and (b) the conversion(s) of the feedstock materials into intermediate and final products. Stage (b) would be divided by direct energy (the exergy) which acts directly on the process materials and agents and the indirect energy, which supports the direct energy (e.g. for mixers, pumps etc; activation energy for reactions, if significant). The EE values in stage (b) would depend on the feedstock materials and the target products. Properties of feedstock materials, such as properties of solids, liquids, gases in their various sub-phases such as crystals, gels, slurries etc; CHO and other chemical content; any water or other carrier; molecular structure and electronics (as in above discussion) and quantities influence the energy requirement. It may be possible to index these properties as part of a multi-criteria assessment using the modelling approaches referred to in section 3.2.3.2 (e.g. fuzzy optimisation), in order to allow technologies to be compared at an abstracted level. The same may apply to properties of final products and the intermediate products necessary to produce them, where product quality is an important consideration. EE comparisons can be fed into LCA input data. Finally, technologies can be indexed for capital and operating costs, with suitable updating (Peter and Timmerhaus, 1991). With this approach, equation (1), which described the generic model emerging from the four tools analysed in this paper, would remain the same, but the evaluation of its variables would be at the higher level of indices rather than specific values.

To our knowledge, USIM PAC from the French company Caspeo (Caspeo SARL, 2019) is the only software package which may offer this more powerful means of selecting advanced technologies for *both* food processing and biorefining.

Partial case studies using the Universal Recovery Strategy have been presented by Galanakis (2015, 2018). UNIFAC was used to identify the best solvent(s) among a group of seven for solubilising each of 15 phenols, found in many forms of FW and other organic materials. The metric for differentiating between solvents was the activity coefficient of both solute phenols and solvents. The activity coefficients in turn were calculated from the feedstock molecule geometry (shape and size) and the energy interaction between the chemical groups and subgroups within the molecule and the molecule itself.

This thermodynamics approach was validated by experimental data in the literature. Subject to defined boundary conditions, it can therefore be used to predict many other optimum phenol-solvent-temperature combinations in the design of improved and more efficient conversions of FW and other organic material. A design for separations involving the 'cascading' of valorisation can also be implemented by first conversions using solvents of higher polarities (hydroalcoholic mixtures) and then with solvents of sequentially reducing polarity. Polarities can be calculated with Molinspiration Cheminformatics, another longstanding software package.

The potential for an index approach to technology comparison and selection needs to be explored in further case studies, which are beyond the scope of this perspective paper.

3.2.5. Life-cycle environmental impact data

SWaVI includes environmental impact categories from LCA, such as climate change potential and acidification potential. It minimises subjective scoring but relies on access to specialist

information in third-party databases for the LCA data, such as ecoinvent. REFRESH and AgroCycle have also provided detailed guidance on using LCA to understand some environmental impacts of FW management and valorisation.

To provide for widespread use, the next evolutionary step needs to be a simplification of the LCA element to enable users to identify and focus on the main or most important environmental impacts. This approach, often called 'streamlined LCA', was first described by Tom Graedel (1998), and was exemplified in the Footprinter software developed from early WRAP research into food waste (Footprinter Inc, 2017). This was used extensively in product development by the multinational Reckitt Benckheiser, among others. The step required is to translate research findings into summary data and a user interface.

The main idea in streamlined LCAs is to focus on the dominant life-cycle stage - where resource use is highest and most intense. Where this is already done, the principle can be applied at the next level, within the selected life-cycle stage, so that the focus of analysis is on the highest environmental impacts (through emissions to air, water or soil) and/or opportunities to be environmentally positive. This deeper level need not be determined from data and analysis, since the LCA and related literature has established patterns of impact from the universe of resource extraction and conversion activities, most of which are known. For example, the impact of individual chemicals is being documented by the EU's REACH and similar legislation around the world. As with technologies, an index system should be possible to derive. The REFRESH guidance takes this approach, recommending evaluation against the four environmental impact categories most used in food LCAs. However, the FORKLIFT tool, through which the REFRESH approach seems most likely to be implemented by most users, limits assessment to GHG emissions.

A significant recent achievement in line with the streamlined approach is the Food Loss and Waste (FLW) Value Calculator, developed by Quantis with input from World Resources Institute (QuantisWorld Resources Institute, 2019). The FLW Value Calculator is currently in its beta version, but it already enables a basic quantification of the environmental impact of managing some FW in common ways such as animal feeding, anaerobic digestion, composting, land application and landfill. The environmental impact categories currently covered by the tool are climate change, water scarcity footprint, land use and eutrophication. The tool also quantifies the nutrient value of the food being wasted. Although the tool is in an initial development stage, needing the inclusion of further, and more specific, treatment options and FW types, along with the generation of more precise and detailed results, it is a great example of a workable tool that can be easily used by a number of stakeholders to screen the environmental performance of FW management, with the potential of including more specific FW valorisation options.

LCA data also needs to be expanded to cover an issue which is not substantively addressed in the REFRESH, WRAP, AgroCycle or SWaVI tools: supporting the carbon and nutrient cycles. The critical question, in relation to any one crop, including grass, of how much of the carbon and nutrient content of the biomass material following crops need for their growth, is largely unanswered at present (Dr Jessica Davies, personal communication, November 2018). This is a big subject about which many papers remain to be written, and links FW and biomass valorisation with other resource cycles such as energy conversions for mobility, heat and power. The tools need to be updated as knowledge from research becomes available.

3.2.6. Improving resource efficiency through Co-location

Integration of disparate knowledge also extends to planning the location of valorisation operations. The location of a plant valorising FW may be an important influence on its commercial viability and environmental footprint. One obvious option is to locate it on the same site as the food manufacturing plant which generated the FW. Whilst this eliminates transportation of the material, it also provides many other opportunities for resource efficiency through the integration of resource use between the two plants. This has been explained in detail by Sheppard et al. (2019).

3.3. Segmentation

The sections above make the case for expansion and integration of knowledge. Now, we argue that this bigger and more ordered knowledge base must be mapped onto small vehicles or platforms for effective delivery, and thereby segmented. By analogy with thermodynamics, the uphill gradient associated with implementation in large scale plants, in terms of cost, effort, skills and knowledge, is too great for the available sources of 'power'. That gradient needs to be lowered.

3.3.1. Modular, mobile, right scale

A major hurdle for commercially viable FW valorisation is the capital investment required in large-scale plants to realise economies of scale. This is a major reason why most of the valorisation pathways researched and technically proven in the numerous research projects funded by national governments and the EU appear not to have been implemented, and why a large proportion of FW from manufacturers still goes to low-value applications. The conventional thinking around the need for scale[1] needs to be challenged. Modular production has long been part of the petro-refining industry (e.g. Honeywell UOP, 2019 (modular refining units); Sulzer Ltd, 2019 (skid-mounted processing units)), often using process intensification, so there should be opportunities for the analogous biorefinery to do the same. The enhanced capability in automation of recent years should improve the likelihood of success.

3.3.1.1. Relative merits of modular production.

In the chemicals industry, ProcessNet, a major European initiative in process engineering, is demonstrating the advantages of modularity in collaborative research projects. ProcessNet defines modularisation as:

> "Designing with standardized units, dimensions or interfaces, which can be easily assembled, maintained as well as flexibly arranged and operated." (ProcessNet, 2016)

Compared to large scale installations, some or all of the following benefits can be achieved with smaller scale, modular plants if the combination of processes and products has the right features.

- Reduced investment risk
  - Simply due to smaller absolute capital requirements
- Flexibility in output volumes, and feedstock and product switching, in response to supply and demand situation

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[1] For example, the following conclusion from the European Commission's Review of the 2012 EU Bioeconomy Strategy (European Commission, 2017, their emphasis): "**Further mobilisation of investments is still needed, which requires a stable regulatory environment**. Existing and new technologies and demonstrators need to be up-scaled and rolled out. Especially private investment in integrated biorefineries, which are capital intensive and are associated with high technological and market risks, require specific support and a stable regulatory environment."

- Matches plant and investment to short product lifetimes (as well as low volumes)
  - Low volume products can be produced in appropriately sized equipment, whilst high volume products can be manufactured by numbering up of production units. Switching is quicker because smaller plant requires less cleaning and preparation.
  - These two features should also minimise the redundancy of equipment in standby mode, because it is more completely utilised.
- Short construction periods
  - Simply because there is less equipment to fabricate and assemble.
- Easier to upgrade technologies
  - Because standardised units can be delivered to the plant and 'swapped in' for the existing unit, rather than assembled into a large plant where welding is required, and the small scale makes delivery and handling easier, with less or smaller handling equipment.
- Greater control in factory environment for construction (Baldea et al., 2017)
- Quicker on-site installation and commissioning
  - Because the entire process can be delivered ready to operate, rather than being assembled on-site. The results of one ProcessNet project demonstrated that systems on a truck could be operationally ready in 40 min, and that exchange of sub-systems was possible in about an hour (ProcessNet, 2016).
- Avoids the negative impacts of large-scale plants (e.g. noise and pollution from logistics operations) (Cristóbal et al., 2018), including through enclosure of operations (ProcessNet, 2016)
- Lower capital and operating costs (Baldea et al., 2017).
  - The ProcessNet F3 project (Bayer Technology Services GmbH, 2013) has shown that these can be realised through lower apparatus, design and installation costs, greater energy efficiency, higher yields by space and time (in two cases by > 100 times) and reduction in solvent use and reaction and processing time.
  - Step-change improvements in selectivity for some processes delivering high added-value products reduce feedstock costs significantly (Double, 2011).

Other issues remain as research questions:

- Is modular plant easier to automate and maintain?
- Do modular plants usually provide a 'plug & play' user experience?

Disadvantages of modularisation, and any negative consequences associated with the above benefits, need to be taken into account in evaluating options; not all processes can be modularised or intensified (Double, 2011). Important variables are the quantity of material processed and the quantity of product (Serna-Loaiza et al., 2019). The case for small scale is stronger if both variables are small or if inputs are small, whilst some large inputs could be processed at a small scale. Numbering up of modules could address the large input/large output case. The case studies from the F3 project and elsewhere show that the development of modular units requires redesign of each of the component processes and equipment used in chemical engineering, intensifying the use of space, time and process agents. However, once done, this new knowledge and specifications can be used with relatively minor adjustments for many inputs and outputs.

A scan through recent articles in the process industry media shows that modularisation is a hot topic. A major driver in chemicals in more advanced economies is to develop and manufacture speciality chemicals, with low volume being compensated by higher prices and margins compared to commodities. Accordingly, plant capacity needs to match the output volume.

Examples of commercial application in process engineering include a collaboration between Akzo Nobel and Italian machine manufacturer Uhdenora in small scale chlorine factories producing a maximum of 15,000 tonnes per year (Scott et al., 2013); and Vogelbusch Biopharma, which, on a new dedicated site, fabricates complete bespoke skid-mounted units for the manufacture of biopharmaceuticals (Vogelbusch Biopharma, 2018).

3.3.1.2. Application to biorefining. This trend in related process industries is opportune, because, as we suggest at the start of this sub-section, small, modular and perhaps mobile valorisation plant may be the most feasible way for FW biorefining to move from experimentation (Technology Readiness Level (TRL) 3–5) to validation and qualification for the marketplace (TRL 6–8). Most importantly, the lower capital investment hurdle (in absolute terms) associated with smaller scale plant supports the business case for FW biorefining.

The potential benefits of smaller scale for biorefining have been recognised in recent research led by Wageningen University, explicitly aimed at innovating to enable viable small scale biorefining of food waste (Broeze and Elbersen, 2016). It led to eight design rules, though none mention process intensification as a means of reducing footprint. The research found that effective innovation involved academics and entrepreneurs being in the brainstorming room together. One interesting innovation from the work was to split the valorisation of apple pulp (from juicing and cider manufacture) between drying or dewatering and the extraction of pectin. Since extraction from non-FW occurs in large plants, it made sense to do the pretreatment such as removal of some or all above-specification water content on a small scale near the point the waste arose, then ship it on more economically. Viable refinements to the small-scale process could later be developed to enable a more integrated process at a smaller scale than the status quo.

Modularity and mobility in biorefining have attracted the attention of the biorefinery research community (such as ProcessNet in the EU and RAPID (AICHe, 2019) in the USA) but have hardly been explored by their mainstream biorefinery industry counterparts. A rare, perhaps the only, example is a startup called Canvas, fermenting spent grain from an Anheuser-Busch InBev brewery in a proprietary process to make nutrient-dense beverages, but is doing it in a shipping container on the brewery's site because of the short quality window associated with spent grain (Caballero, 2017).

In food manufacturing, a close sub-sector, Mondelez has adopted modularity wholesale in its 'Line of the Future' process redesign introduced in 2015 (Mondelez International, 2015 and personal communication, March 2017).

An essential requirement for the wide adoption of most technical innovations is the development of standards. The ICS (International Classification for Standards) category 'Production in the Chemical Industry' has only 18 standards, and none for modularity. None of the 21 standards across ICS categories addressing 'modularity' involve process engineering. The Association of German Engineers (VDI) is currently defining standards for modular process engineering (VDI, 2017).

Research and development in modularisation for biorefining will involve a mix of applying processes already proven in projects such as F3 and intensifying additional processes for which there is no precedent or which are specific to biorefining.

An important question is whether biorefineries, and more specifically FW valorisation processes, have any significant differences from petrorefineries which might act as a barrier to viability. We

have identified the following differences:

a) Challenges
  1. Greater range of chemical composition in FW feedstock
  2. Need to control action of oxygen content in FW
  3. Significant variations in availability and quality of feedstock

These differences do not present unsolvable problems. The availability issue is less to do with the engineering of processes, but is a real challenge for which modularity is a compelling solution because it allows plant scale to be adapted to volume. Section 3.4.1 addresses this, discussing a business model which is both mobile and modular.

b) Opportunities
  - Wider range of process technologies possible with FW, including biotech and non-solvent.
  - Less need for pretreatment of FW (e.g. deconstruction prior to molecule assembly − the equivalent of cracking).
  - Lower temperatures and pressures for processing FW.
  - FW involves safer process agents and products.

Opportunities 2−4 enable lower cost.

The following are suggested important enablers to support modularisation, drawn from the innovation literature and our experience of supporting technology commercialisation:

  - Aim initially for single feedstocks, product outputs and processes.
  - Deploy where FW feedstock is free and preferably where the feedstock owner is currently incurring a cost for disposal.[2]
  - Accept sub-optimal processing in first commercial iterations.
  - Identify non-conventional markets for process products wherever possible.
  - Evolve the system quickly into next generation versions.
  - Ideally make it mobile.
  - Ensure the smaller scale equipment is robust (ProcessNet, 2016) or innovate by process integration to ensure it is.
  - Innovate around limitations on thermal separation steps imposed by small scale.
  - Design modules around the 'Minimum Processing Scale for Economic Feasibility' (Serna-Loaiza et al., 2019) with the best available technologies.
  - Ideally enable sub-module swaps from the beginning so that there is some choice about processes and products.
  - Build up a strong customer pipeline.

This is a part-specification for research and development in this field.

A perhaps surprising implication of the modular and mobile approach is that the comprehensive, cascading model for biorefinery design, whilst still the end goal, is not the most effective starting point. Standalone, single-product conversions (e.g. pectin extraction from citrus peel), performed at the small scale and in modular and particularly mobile equipment, may provide the low cost necessary to generate revenue and prove performance so that a viable basis for further development is created. That further development should involve gradual addition and integration of processes to more fully valorise the feedstock, and such growth is made possible by the modular and mobile nature of the original setup.

3.3.1.3. Supporting dynamics. This conception of technology evolution is supported by the widely accepted work of Clayton Christensen at Harvard in his analysis of innovation and adoption patterns in a number of industries, known as *The Innovator's Dilemma* (Christensen, 2000). Part of the thesis he proved is that disruptive innovation is in most cases carried out by smaller companies independent of the risk aversions of larger companies, and it often produces simpler products or systems with less functionality or quality than the incumbents. However, it gains a foothold because it meets a market need which has been discounted or not recognised by the dominant suppliers. In time, the disruptive innovation improves and surpasses the incumbent (Christensen, 2000).

These dynamics point to a development path of the industry which would start with modular, perhaps mobile, single-process valorisation at many sites, gradually adding modules for different products and so becoming biorefineries, with frequent process improvements as learning accumulates and is shared.

Support for this approach also comes from the economics domain. Michael Porter's seminal research on the development and value of location-based clusters of economic activity and expertise (e.g. Delgado et al., 2016) suggests that the seeding of FW valorisation through low cost modular equipment on food manufacturing sites would gradually attract a set of complementary activities and skills around those sites which in turn would support the evolution of the modular units into biorefineries, capable of converting different local FW streams as well as ligno-cellulosic biomass. Such clustering could be accelerated through policy measures.

3.4. Co-ordination

Widespread adoption of FW valorisation, particularly through modularisation, carries the risk of inefficiencies arising due to the conflicting actions of independent operators − much like the growth of the railway system in nineteenth century Britain. To avoid this, either the independent developers and operators need to be galvanised by common incentives and threats such that their goals and actions converge, or co-ordinating entities are needed − or a combination of both. The following discusses two possible mechanisms.

3.4.1. Business model

There is now a large research literature on the question of whether greater sustainability can be achieved by the sale of functionality as a service rather than embodied in an asset. The essential difference is ownership of the asset which provides the functions desired by the customer.

In FW valorisation, Biorefining-as-a-Service (BaaS) could provide a number of efficiencies:

1. Concentration of expertise: A company specialising in biorefining, or more narrowly FW refining, could be far more efficient than individual site managers with varying degrees of expertise making arrangements for the work. This would correct a weakness in WRAP's Mapping Tool, whereby it is directed at the wrong people (site managers or miscellaneous others who may be given the responsibility by their employers).
2. Location: BaaS could be operated much like an energy services company operates combined heat & power plants located on client sites.
3. Modular: The expertise of the service provider would enable quick switching or replacement of modules to respond to feedstock variations or changes in market demand.

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[2] Following the F3 project, Arkema was not able to commercialise its successful solvent-free glycerol-to-acrylic acid process because the cost of glycerol was uncompetitive against the cost of propylene used in the incumbent process.

4. Mobile: BaaS is the right model for servicing food processing and manufacturing sites with less constant and lower quantities of FW, using modular plant also designed to be mobile.

An internet search indicated that BaaS has not been coined as a term before. Its feasibility needs to be explored in research and development.

3.4.2. Innovative finance

With capital and some operational costs cited as a main barrier to adoption of FW valorisation systems (e.g. European Commission, 2017), it is assumed that the owner of the FW or a developer looking to set up a processing site needs to find the money. However, finance innovations relating to energy have lowered the risk for third party investors and there is no reason why these could not be applied to FW valorisation and biorefining more widely.

Investment in energy efficiency (EE) technologies and measures for buildings and industry is retarded by a number of barriers, two major ones being the cost of such investments and competition for capital funds with other priorities of the company. An obvious way around these barriers is to source the funds externally, which maintains capital funds for other purposes and enables reduced payments for energy, associated with the savings involved. However, this raises further barriers, two of which are, for finance providers, the quality of the EE project and the associated risk of not achieving the predicted savings, and the variations in size and features of EE projects, which make due diligence costly.

A widely-supported solution to these and other financing barriers is the Investor Ready Energy Efficiency (IREE™) scheme (Investor Confidence Project Europe, 2019). The IREE™ was developed by a large US initiative called the Investor Confidence Project, and it has since been supported in Europe with EU funding. In short, the IREE™ provides a protocol by which prospective EE projects can be assessed by IREE™-qualified parties, so that lenders and investors, channelling funds in any of a wide range of financing arrangements, can have confidence in achievement of planned returns, reduce due diligence costs, and, importantly, can bundle smaller IREE™-certified projects together into an investment package of commercially-viable scale.

For FW valorisation, the same uncertainties apply. Newer, more energy- and materials-efficient technologies may need validation for particular feedstocks and/or target products; where target products are food, feed, pharmaceuticals or other products with a safety implication, they need qualification because of the raw material source. Further research and development could support the adaptation of the IREE™ for FW valorisation, including in modular form.

3.4.3. Demand-side Co-ordination

BaaS and innovative finance are models which the supply side could offer to accelerate improved valorisation of FW. If the enhanced decision-making tools described in this paper were used by an industry acting collectively (e.g. through an industry body), the following benefits would be enabled:

- Optimise size and locations of valorisation plants in economic, environmental and social terms.
- Switching of valorisation pathways across the sector estate according to feedstock quantities and market opportunities, including expansion or contraction in the amount of feedstock valorised and the number of types of outputs produced. This would smooth out seasonal and quality variations across sites.
- Enable access to more investment funds at a lower cost (freeing more funds at individual companies for investment in competitive aspects of operations and products).

In such a scenario, resource efficiency would be removed from the scope of competition, making it pre-competitive, and enabling competitive energy to be focused on product value for money issues.

If used by national policymakers, such co-ordination would:

- Inform regulatory impact assessment in designing policy to support action by a whole sector.
- Inform economic planning by quantifying estimated economic gains at sector level.
- Inform integration with wider policies:
  - Ecology
  - Climate change
  - Circular Economy
  - Economic security.

An alternative to implementation through co-ordination is through competition. An early mover would gain a competitive advantage, but this would prompt others also to invest, eventually achieving the jump to a new innovation curve. However, this is an inefficient way to do it.

Relevant precedents for pre-competitive industry co-ordination are:

- Climate Change Agreements (CCAs) — In the UK, CCAs are co-ordinated by industry bodies and give companies an 80% discount on the Climate Change Levy (CCL) in return for commitments to reduce greenhouse gas emissions by agreed targets and dates. The UK Food & Drink Federation and eight other sub-sector associations manage CCAs.
- SPIRE — This is a public-private partnership between the EU and the European process industries whose mission is "to ensure the development of enabling technologies and best practices along all the stages of large scale existing value chain productions that will contribute to a resource efficient process industry." SPIRE stimulates and co-ordinates research & development projects within the Horizon 2020 funding programme.
- Oil & Gas Technology Centre — The Centre is an industry initiative supported with some public funding, whose purpose is "to deliver, accelerate, stimulate and inspire innovation between industry, academia and government to help maximise economic recovery from the UK sector of the North Sea."

This top-level argument needs to be validated with studies which generate or gather data from pilot co-ordinating activities which is then compared with data representing the status quo. It is therefore a field for further research.

3.5. Conclusions and next steps

Four tools emerging from the research community on how FW can be valorised in an optimum way have set a new level of quality for the management of such material. They have the level of rigour amenable to conversion into an international standard. However, our critique has concluded that the knowledge content of the tools and the engagement they require of users are not powerful enough to make much of a practical difference on the ground.

We have identified elements of a context-free process design system which would enhance the effectiveness and productivity of the tools, and which form the evolutionary trend necessary to make that practical difference.

The system elements identified and described are in various stages of development, as summarised below:

- The Galanakis framework is fully described but not fully populated with content (including referenced content), and, from available information, has hardly been implemented
- the use of CAMD has generated a significant amount of content, which is available in software, but data relevant to food waste and wider biomass feedstocks is not available in that software or is too disparately stored to be widely used
- technology characterisations have not reached an ontological level by which indexed parameters of different technologies can be compared with respect to indexed feedstocks and products
- LCA is also not elevated to an ontological level with respect to valorisation pathways, to enable rapid identification of potential issues with process options; modularisation, optionally mobile, offers promise as a low barrier entry and expansion point for wide adoption of FW valorisation systems, but requires the development of basic module processes achieved through process intensification
- Biorefining-as-a-Service (BaaS) would enable deep expertise in FW valorisation to be available to FW owners, streamlining the system and boosting efficiency, effectiveness and economy; assured finance schemes to provide quality opportunities for investment in small and large valorisation systems would minimise the financial hurdle associated with valorisation of bio-resources, but the details need to be transferred from other validated fields of application such as energy efficiency
- Finally, pre-competitive co-ordination in the development and application of the enhanced tools and initiatives described in this paper would support accelerated and cost-efficient implementation, but needs to be validated with research into prototypes of co-ordination.

This analysis provides a sketch of the research and development landscape ahead, including validation through case studies, if we are to return, in modern society's highly co-ordinated industrial activity, to a system in which bio-resources are used in a continuous cycle of maximised functionality.

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