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Synergies in the co-location of food manufacturing and biorefining

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ABSTRACT

In food and drink manufacturing, costs must be relentlessly minimised because margins for most products are low. At the same time, the business case for biorefining of lignocellulosic feedstocks has been positive in only a small number of cases. Since the two industries use similar feedstocks and processing equipment, there should be potential for significant sharing of resources for economic and environmental gain, particularly with regard to energy, if they were co-located. This paper reviews the nature, issues and opportunities for this sort of resource sharing between food industries and biorefineries. It then illustrates the opportunity by modelling a food product (coffee bean roasting) co-located with lignocellulosic biorefining of its downstream by-product (spent coffee grounds) where biofuels are not the target output, identifying and evaluating the resource efficiencies and economics involved. The analysis shows that there can be significant benefits, but that the exact nature of the food and biorefinery products and the biorefining pathways are the key dependencies. Further research should produce a comprehensive league table of co-location opportunities for the benefit of both industries to enhance both their economics and their sustainability metrics through well-targeted synergies.

1. Introduction

Food and drink (F&D) manufacturing in industrialised countries is a large sector by value and volume, accounting for a significant proportion of energy consumption in the manufacturing sector – 11% in the European Union (EU28), for example (Eurostat, 2018) – even though its energy intensity is moderate. The sector has improved energy efficiency significantly since the introduction of relevant European legislation (reduction of 12% in energy intensity in the EU28 between 2010 and 2016 (Enerdata, 2018)), and is progressing towards its 2020 targets. This has been achieved through the gradual implementation of well-established technologies and measures. Radically more efficient technologies are also known, and cost and confidence issues associated with their practical implementation and deployment on a wide scale are being addressed.

Overall Equipment Effectiveness (OEE) can also contribute to energy efficiency by seeking 100% Quality (of outputs), Performance (speed of output) and Availability (of machinery). However, OEE focuses on optimising the operation of equipment as designed rather than introducing design or process innovation. Lean Manufacturing has a role in supporting energy efficiency, through the elimination of four of the wastes it addresses: Motion, Waiting, Overproduction and Defects (Bicheno and Holweg, 2016). These are mainly concerned with trimming back activities, and are complementary to two additional approaches that focus on enhancing current activities: identifying under-use of resources and increasing the functionality of existing resources.

In considering the under-use of energy, the main question is whether the energy infrastructure and waste energy in F&D manufacturing could be used once an F&D manufacturing process has been optimised as far as commercially possible. One possibility is the use of the energy and other resources (materials, water, process agents, transportation, labour, intermediate and final outputs and infrastructure assets (for energy generation and conversion, production equipment and storage)) in complementary manufacturing processes. The emerging field of lignocellulosic (LC) biorefining fits this description. To date, most LC biorefining projects and commercial ventures have been designed to produce biofuels as the main output. However, this sub-optimises both the functional and economic potential of the input resources, because biofuels are among the lowest value outputs possible, and they incorporate many compounds that could have a highly valued use in other applications (US Department of Energy, 2004, 2007, which were the first comprehensive studies of viable biorefinery outputs; Budzianowski, 2017, promoting a cascading model of biorefining conversions according to output value; Campbell et al., 2017, supporting biorefining which integrates resources including wastes).

The focus on biofuels, without the benefit of additional high value streams beyond mainly animal feed, has meant that only a limited number of biorefinery ventures have been commercially successful. A more viable approach is to follow a cascade model (Budzianowski, 2017) in which the maximum fraction of bio-inputs is converted to the highest possible market and societal value (e.g. jobs created, product functionality), and the remaining fractions, including the by-products from the first outputs, are progressively converted to lower value outputs. Possible outputs include food products, most of which rank alongside chemicals and engineering materials in terms of market value. This cascade model approach is also supported in EU research and development programmes (European Commission, 2017).

An LC biorefinery is somewhat analogous to a petrochemical refinery, as shown in Fig. 1. The sequence involves the breaking down of molecules and then synthesis of new molecules. Pretreatment breaks up the polymeric LC structure into sugars so that chemical building blocks mainly in the C2-C6 range – e.g. lactic acid, levulinic acid (the equivalent of commodity chemicals) can be synthesised. Thermochemical pretreatment, the predominant current approach, often demands the highest energy input in a biorefinery and, together with hydrolysis, is the equivalent of cracking in a petrorefinery. The chemical building blocks can be assembled into a wide range of molecules at the 'Secondary Chemicals' level (e.g. acrylates, esters). In a wide range of reactions, these in turn can be synthesised into Intermediate materials and agents (e.g. polyacrylates, polyethers), which can be manufactured into industrial and consumer products.

Pairing food manufacturing with LC biorefining to realise resource synergies could improve the energy and other resources efficiency of both industries, and provide a market for some of a cascading biorefinery's outputs.

Therefore, the thesis investigated in the current research was:

Potential synergies between F&D manufacturing and fractional biorefining of lignocellulosic materials, together with the value of their outputs, make co-location of facilities commercially and environmentally attractive.

The associated research questions were:
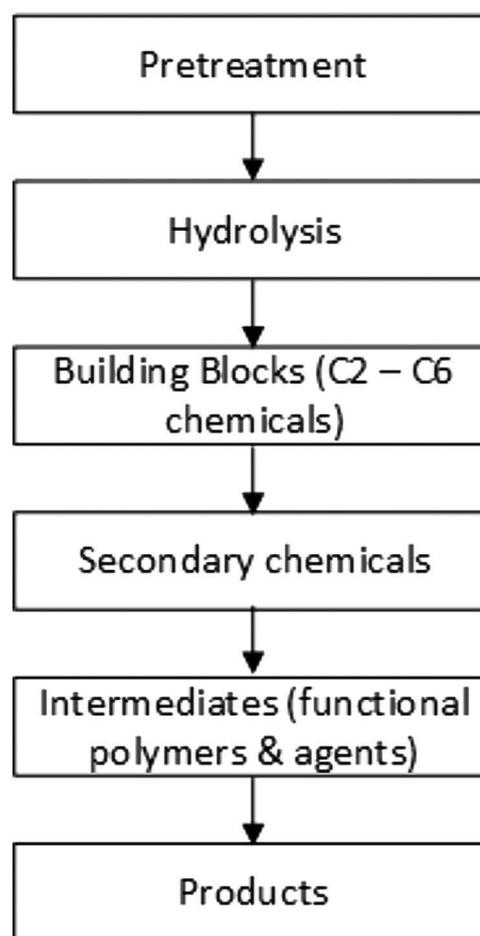
Fig. 1 – Schematic of Biorefinery Processes (US Department of Energy, 2004).

1 Does this proposition hold true for a selected type of food product as a case study?
2 What are the projected financial benefits?

Whilst environmental benefits have been identified in the research, the deeper research question – quantifying and characterising the projected environmental benefits of co-location in terms of resource use and impact reduction – requires a dedicated life cycle assessment.

The remainder of this paper reviews relevant previous work (Section 2), sets out the technical and economic theoretical bases for the thesis (Section 3), and then addresses the research questions through a case study (Sections 4 (Methodology) and 5 (Results and Discussion)).

2. Previous work

To our knowledge, this idea has not previously been proposed or investigated explicitly, though the previous work reviewed in this section at times alludes to it and could have been extended to include it.

Perhaps the best example of industrial bio-ecology has been at sugar refineries (Clauser, Gutiérrez, Area, et al. (2016) - modelling output viability against scale; Short et al. (2014) - describing British Sugar as a case study), but this has involved the adventitious exploitation of resources arising from the sugar refining rather than a system designed with co-location in mind.

The processing of cashew nuts by both indigenous people and modern industry is a good example of food processing and biorefining, although sub-optimal because the available resource synergies are not exploited. Typically, cashew nuts are harvested and the highly caustic oil within the shells is released on the farm, then the two materials streams go their separate ways. The oil is used in the automotive industry to make items that can withstand friction and heat resistance such as brake linings and clutch discs, and products such as acid-resistant paints, resins, varnishes, enamels, black lacquers and mouldings. The cashew tree also yields a resinous, sticky gum, cashew tree latex, which can be used in place of gum Arabic. The gum can also act as a binding agent in the pharmaceutical industry for capsules and pills, a food stabilizer for juices, and in the production of cosmetics (Agriculture Nigeria, n.d.; Tanstia - FNF Service Centre, 2011). The industrial ecology model proposed here would have the intact nut and shell as harvested, as well as the tree latex, delivered to the food/biorefinery site, where the nut and oil would be separated more efficiently, with resources such as energy being optimally used, while the oil and latex could be processed according to market demands and commercial advantage.

There are many models for biorefining processes that use avoidable or unavoidable food waste materials (see for example Garcia-Garcia et al. (2019a) and the research projects funded by the EU listed in European Commission (2017), Sections 10.2 and 11.10). However, to our knowledge these all involve dedicated biorefining sites away from the F&D manufacturing site where the waste might have arisen. The multiple benefits of co-location described in this paper cannot therefore be realised.

Christensen and Kjaer (2009) explored the concept of industrial symbiosis involving biomass including food by-products, but restricted the concept to the production of biofuels and other types of energy, and to the use of materials rather than all resources. Jungmeier et al. (2014), reporting for the IEA Bioenergy Task 42 (Biorefining), concluded that the food and feed industry could viably and feasibly "additionally produce bioenergy carriers." Their analysis was restricted to a template process starting with a mechanical step followed by a chemical step, but with no biological steps. Tsakalova et al. (2015) built a decision support tool for identifying the most attractive feedstocks, processes and outputs for biorefining, saying that previous work had looked at specific instances of these and not taken a system view to generate a model that could be applied to any situation. Moncada et al. (2016), referencing two previous works, concluded that "the integrated production of chemicals, materials, energy and food is probably a more efficient approach for the sustainable valorization of biomass resources in future bio-based economies." They set out the principles of hierarchy, sequencing and integration (of all resources including energy and materials) in the design of a biorefinery, but only referred in passing to the integration of F&D manufacturing and biorefining. Parajuli et al. (2015), reviewing sustainable pathways for biorefinery value chains, said that "about 40–60% of the total operating cost of a typical biorefinery is related to the feedstocks chosen". If correct, this supports the value of not only sourcing biorefinery feedstocks from by-products arising from F&D manufacturing on the same site at a negative cost due to eliminating waste collection charges, but also sourcing LC feedstocks that may be associated directly or indirectly with the incoming food ingredients, such as straw.

An EU-funded project, BIOCORE (2010-14), investigated the merits and disadvantages of centralised versus distributed biorefining using a proprietary organosolv pretreatment, but without reference to food production. Their Total Site Analysis (TSA), which included Pinch Analysis, indicated that "savings from process-to-process integration may range from 14 to 85%, and that savings increase as the number of products increase." The range of savings indicated that "the magnitude of the savings supported scenarios with co-located production" (O'Donohue, 2014). Energy was a major part of these savings, along with water and materials. The limited literature on process integration in industrial symbiosis has also reached the same conclusion, e.g. Hiete et al. (2012), using thermal pinch analysis to assess benefits between co-located companies, but not biorefineries; Kantor et al. (2012) – modelling process integration in a small eco-park involving chemical engineering companies, but not biorefineries.

In a programme of research producing a series of publications, Campbell and colleagues have championed the extraction of arabinoxylans (AX) from lignocellulosic material within a biorefinery context, highlighting the synergistic opportunity to create a new class of food ingredients from such feedstocks, and emphasising the importance of process integration with respect to other biorefinery products (Du et al., 2009; Misailidis et al., 2009; Martinez-Hernandez et al., 2013; Campbell et al., 2017; Alyassin, 2016; Martinez-Hernandez et al., 2018; Campbell et al., 2019). As Martinez-Hernandez et al. (2018) note "the opportunity to extract AX in a biorefinery in order to remove it from the animal feed chain, where it is not needed, and divert it into the human food chain, where it is needed, represents a synergistic win-win situation." This is entirely in line with, and comes closest to, the concept proposed here, but focuses on only one aspect rather than the full benefits of co-location.

The proposition in this paper is that these benefits can be extended from within biorefining to the co-location and integration of F&D manufacturing with biorefining. The concept presented applies many of the green biorefinery principles set out by Moncada and colleagues (Moncada et al., 2016).

3.   Resource synergies

This section identifies the synergies in the use of resources that in theory should be realisable between co-located food and biorefining activities. These are converted into specific resource synergies in the case study (section 4).

3.1.   Energy synergies

3.1.1.   Introduction

Both F&D manufacturing and LC biorefining process organic renewable material using chemical engineering processes and equipment. LC biorefining usually involves a pretreatment process to overcome the recalcitrance of cellulose, hemicellulose and lignin to attack by chemical or microbial agents, by separating large portions of the three polymers, so exposing them to hydrolytic agents. Downstream biorefining can produce higher quality products and be more efficient if the main constituents of the feedstock – typically in the proportions cellulose ~40%, hemicelluloses ~25% and lignin ~25% – are separated first rather than processed together (Brandt-Talbot et al., 2017). Pretreatment methods range from high thermal inputs (e.g. steam explosion) to harsh chemicals at relatively high temper-

atures, to low temperature inputs with enzymes, ionic liquid solvents and targeted energy inputs such as microwaves.

Biorefining for chemicals, materials and food is likely to become more targeted on specific reactants and reactions (Petridis and Smith, 2018), using biological agents, catalysts and solvents and more efficient, targeted energy sources such as microwave and laser – all amounting to the greater use of 'precision engineering', enabling operation at ambient and low elevated temperatures, therefore without much waste heat. This follows the technology trend of 'Macro-to-Nano' identified in the TRIZ innovation methodology, based on many empirical observations of science and engineering innovations (Mann and Dewulf, 2002; Mann, 2007). Precision engineering does not preclude the use of process intensification – involving high temperatures and/or pressures over short and very short periods – where it can deliver greater efficiencies. The following analysis therefore includes only these milder pretreatment methods, referring to them as 'precision LC biorefining'.

It is important to have a theoretical understanding of the potential synergies in advance of spending time and money on modelling and measurement. Potential thermal energy synergies are considered first. The analysis uses the broad representation of food manufacturing and LC biorefining process stages shown in Fig. 2.

3.1.2. *Thermal energy*

Energy used in thermal treatments is related to:

- Bond dissociation
- Activation energy
- Heat capacities of energy carriers and phase changes (latent heat of vaporisation, ΔH_{vap}), particularly water as both a process agent and inherent in the subject materials
- Conversion efficiencies from energy source to means of delivery

The minimum theoretical energy (the exergy) required to effect changes in the subject materials is the sum of bond strengths and activation energy. Delivering activation energy involves losses incurred with the last two items above. The third item is a far higher contributor to the total heat requirement than the other three.

What is the general scope for waste heat exchange respectively within and between food manufacturing and LC biorefining processes? The answer requires a listing of the heat loads in each industry and, for each, values for the main thermodynamic variables in bands or categories of high, medium and low:

- Temperature of the energy carrier
- Heating, heat retention and cooling periods
- Pressure
- Mass and flow rate of energy carrier
- Mass of processed material

Temperature levels and gradients are also important for understanding the functional value of the heat, the amount that can be transferred and at what rate.

The potential for retaining and recycling heat within the same load is also important. Water, with over four times the heat capacity of air, a liquid phase that consolidates heat and enables easier transfer, and higher heat transfer coefficients, offers more potential than air for retention and recycling.

Within the scope of this paper, we can list the loads and associated temperatures, assume atmospheric pressure for most loads and, for each load, distinguish between water and air as the main thermal energy carriers. Differentiating loads by masses and flow rates is beyond the scope.

With the above assumptions and limitations, Table 1 is therefore an initial rough indication of where the highest enthalpies are in each industry using mainstream technologies.

Precision LC biorefining using bio/chemicals involves the copious use and heating of liquids to relatively low temperatures (120 °C in the case of the ionoSolv process modelled in this paper). The quantity of liquids involved is high (8 parts ionic liquid and 2 parts water to one part biomass for ionoSolv). The heat capacity of the ionic liquid, triethylammonium hydrogen sulfate ([TEA][HSO4], CAS 54272-29-6), which to our knowledge has not yet been reported, is probably high. There are also subsequent multiple separation/purification and drying stages that require relatively high energy inputs, whether or not the technical means involve thermal energy. However, once heated, the liquids can remain in the system for repeated cycles or downstream processes, so the heat capacity plus good thermal insulation significantly reduces the energy input required.

At the LCB Syntheses end of the biorefinery, chemical building blocks are converted to secondary chemicals and intermediates (functional polymers and agents) in mainly exothermic reactions. The main processes involved are oxidation, aldol condensation, isomerisation, hydrogenation and hydrogenolysis, with heat of reactions in the range – 40 to – 200 kJ/mol (Chheda et al., 2007). Fig. 3, from Chheda et al. (2007), shows the approximate range of temperatures and pressures applying to catalysed carbohydrate conversions.

Whilst exothermic reactions make a small contribution to heat available for other processes, the temperatures for catalysed synthesis from carbohydrate building blocks in the liquid phase (the 'precision biorefining' we are focusing on in this paper), which are mainly in the range 80–200 °C, mean that significant waste heat is available. In addition, elevated pressures are used, as shown in Fig. 3. Compressors are at best 15% efficient, providing significant waste heat at temperatures useful for reducing heat inputs. In addition, where pressure is allowed to fall during periods of non-production, there is scope, subject to economics, for conversion of the energy in the expanding air to heat or power.

3.1.2.1. *Net flow.*

The scope for waste heat recovery and reuse in F&D manufacturing has been estimated at between 15% and 50% of the waste heat generated (Seck et al., 2013). In LC biorefining, there is a wide range of potential, up to 98% if confined to pretreatment only Baral and Shah (2015). In assessing the value of the co-location suggested in this paper, the values of that heat reused respectively in F&D and LC biorefining processes need to be carefully assessed.

In a heat integration network for a linear process, there is a heat cascade. Integrating heat recovery and reuse between two processes (F&D manufacturing and LC biorefining) takes the form of a heat loop.

Table 1 indicates that the greatest loads in each industry are:

F&D: Anything involving radiant or convected heat and drying.

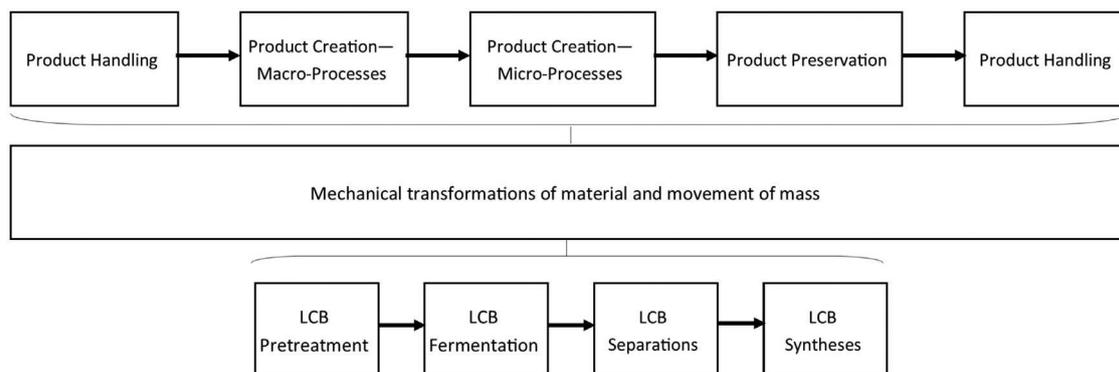**LC biorefining**: Anything involving drying and product synthesis.

Fig. 2 – Schematic representation of F&D manufacturing and LC biorefining production stages.

Table 1 – Temperatures of heat carriers in F&D manufacturing and LC biorefining processes as an indicator of respective enthalpies.

F&D THERMAL ENERGY LOADS

Process	Subject of Inefficiency	Example	Heat Carrier Temperature Range (°C)
Product Creation: Macro-Processes			
Evaporation	Water	Concentration of sugars	100
Distillation	Alcohols	Spirits	70-80
Product Creation: Micro-Processes			
Cooking	Water	Vegetables	100 - 110
Baking	Air, inherent water	Bread	180-550
Toasting	Air	Flaked cereals	270-330
Product Preservation			
Drying	Air, surface & inherent water	Powders	120 - 180
Sterilisation	Water (steam)	Canned goods (retort)	110-135
Pasteurisation	Water or heat transfer fluid	Fruit juice	100-140

LC BIOREFINING THERMAL ENERGY LOADS

Process	Subject of Inefficiency	Example	Heat Carrier Temperature Range (°C)
Pretreatment	Solvent, Water	ionoSolv	120
Fermentation	N/A	Yeast, enzymatic	35-65
Drying	Water	Separation (e.g. hemicellulose from lignin)	120-180
Synthesis of Chemicals			
Building blocks to secondary chemicals	Water & other binding liquids	See Fig. 3	See Fig. 3
Secondary chemicals to intermediates	Water & other binding liquids	See Fig. 3	See Fig. 3

This and the temperature gradients indicate that excess heat could be captured and reused in a loop of F&D 'Micro-Processes' and 'Product Preservation' to LC biorefining 'Pretreatment' and the LC biorefining 'Drying Steps' and 'Syntheses' to F&D 'Macro-Processes'. This would enable the two production lines to be located in a loop rather than parallel, as shown in Fig. 4.

These physical locations may be important for maximising the efficiency of heat transfer.

The flow in general from F&D 'Product Creation – Micro-Processes' to 'LC Pretreatment' is also predicted by the Boltzmann equation ($S = k \bullet logN$), where S is entropy,? ? is the Boltzmann constant (equal to 1.38065×10^{-23} J/K) and N is the number of microstates of the material, given by the number of molecules in a defined micro-volume of the total volume occupied by the material. Thus, entropy is higher as molecule size decreases. The size of food molecules as reactions are actuated during cooking and other treatments is likely to be generally smaller than the size of lignocellulose molecules during pretreatment, partly because the latter are bonded in polymer chains.

Galanakis (2017) suggests that a variation of Boltzmann could be used for modelling food and bioproducts processing, replacing the use of Monte Carlo and other stochastic tools. His variation expands N to W, defined as the number of possible events, arrangements or microstates, and exemplifies this with a case study of starch hydrolysis in which the model closely follows experimental results. Again, the number of events (e.g. collisions) is likely to be higher in food processing because molecules are generally smaller and there are more and shorter processes. The breakdown stages of non-electrical precision LC biorefining tend to involve relatively long periods of inaction whilst solvents and/or microbes do their work.
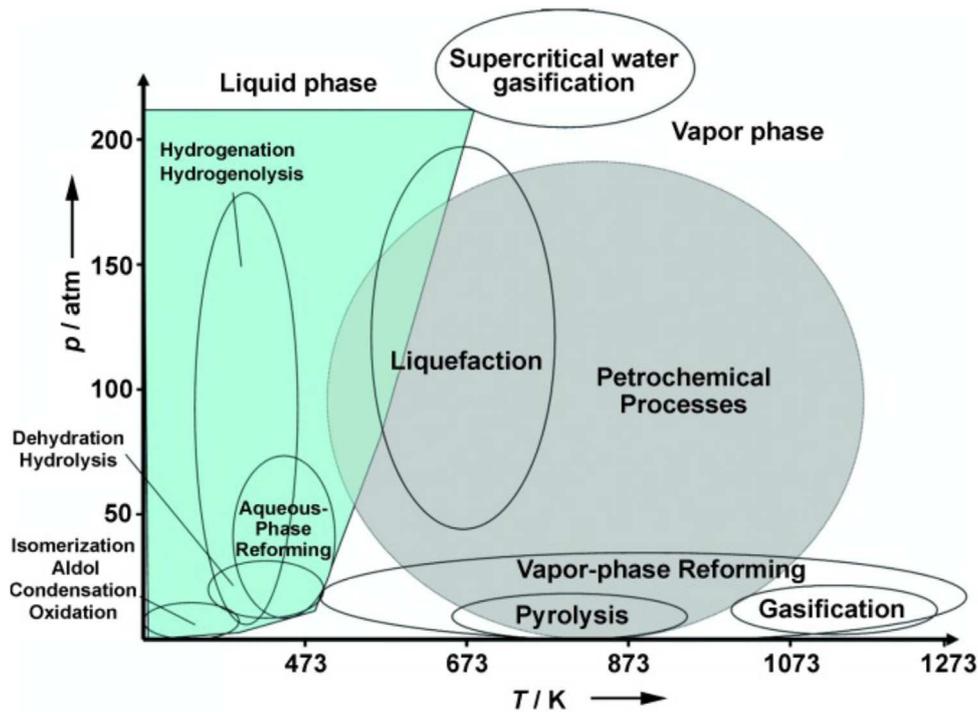
Fig. 3 – Approximate reaction conditions for the catalytic processing of biomass-derived carbohydrates (most in the liquid phase segment) compared to thermal treatments and petrochemical processes. Chheda, J. N., Huber, G. W., & Dumesic, J. A. *Liquid-phase catalytic processing of biomass-derived oxygenated hydrocarbons to fuels and chemicals.* Angewandte Chemie - International Edition, 2007, 46 (38), 7164–7183. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.
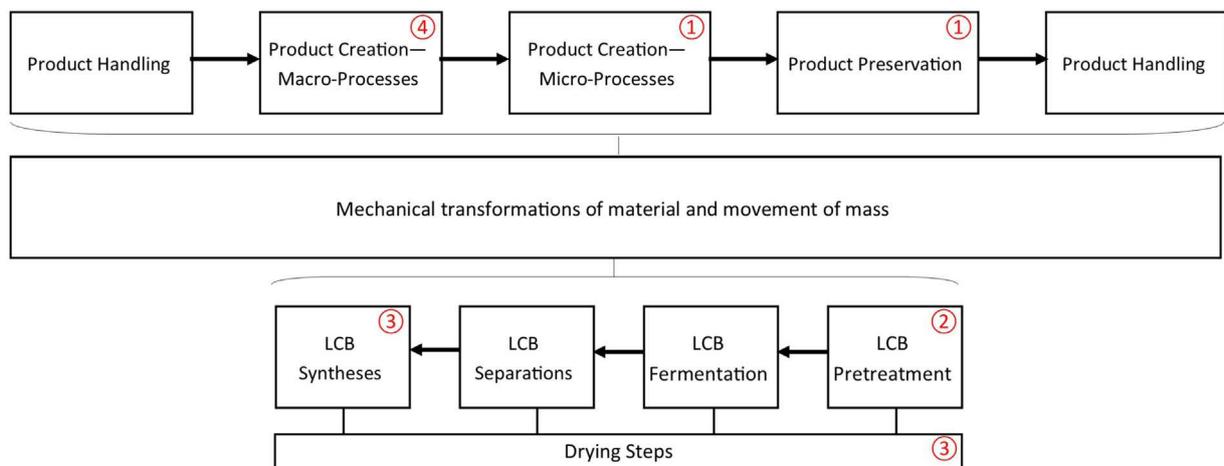

Fig. 4 – Schematic representation of F&D manufacturing and LC biorefining heat loop *Heat flows are from ① to ② and from ③ to ④.*

To assess the thermal energy synergies in any one case, the methodology set out by Woolley, Luo, & Simeone (2018) brings together all the above variables into a set of equations.

3.1.2.2. Future efficiencies through technical innovation. An important influence on assessing the value of co-location are technology innovation trends. In both F&D manufacturing and LC biorefining, the trend is towards precision application of energy, with no loss of product quality. For baking ovens, research is indicating that significantly lower energy inputs are possible using alternative fields, particularly infrared and microwave (although surprisingly, to our knowledge, there is only one report with actual data (Martínez-Bustos et al., 1999). In LC biorefining pretreatment, microwave pretreat-

ment, alone and in support of more mature technologies, has been demonstrated to be more energy efficient than a traditional acid-assisted thermal method (Garcia-Garcia et al., 2019b). The precision design and use of pretreatment solvents is being improved, reducing the use of water because it is a poor solvent for cellulose (Petridis and Smith, 2018). The trend is therefore a move away from thermal energy carriers such as water and air towards the direct application of thermal and electrical energy to the process material. 'One-pot' biomass conversions to end products are also being researched (Clarke et al., 2018).

This trend towards precision heating obviously reduces the scope for heat synergies in co-location. However, it opens the potential for other synergies, which are explored in the next section.

3.1.3. Non-thermal energy

Non-thermal energy is in practice electrical energy, but in theory includes optical, sonic and plasma fields. These could be part of the process innovations mentioned above.

In the process schematic shown in Fig. 4, the electrical energy loads are summarised in terms of their functions of mechanical transformations of process material and the movement of their mass. These include:

- Product Handling: functions such as the delivery of ingredients and production agents at the front end and product logistics at the back end, and the movement of materials through production stages.
- Product Creation – Macro Processing: Mechanical size reduction, separations, mixing and forming.
- Product Preservation: Mechanical dewatering, compression (for refrigeration), electromagnetic fields, application of coatings, and packaging.
- Product Safety: Operation of cleaning and sterilisation equipment.

Electricity cannot be shared directly as with thermal energy, but synergies between processes can be found in the infrastructure that delivers and stores it. The following analysis draws on well-known aspects of electricity generation, supply and conversion systems.

3.1.3.1. Energy generation & supply infrastructure.
Grid-connected factories need sub-stations. These can be more affordable because of the greater revenue generated from the same site.

Greater concentration of electricity use makes on-site generation more viable, with or without a grid connection. As heat is also a major requirement, combined heat and power (CHP) is an obvious consideration. The economics of CHP are driven mainly by the need for a minimum heat requirement, and this is more likely to be met with co-located processes.

Concentration may also improve the economics of process intensification using power-dense technologies such as pulsed electric fields (PEF) and high pressure processing (HPP).

A higher concentration of processes also makes participation in electricity capacity markets more possible. Industrial users can reduce or shift their non-critical loads to enable the grid to avoid use of peak generating capacity, in return for a premium payment.

On-site generation, including through renewables, opens the potential for an on-site 'private wire' network or connection as part of a local minigrid. Both of these enable reductions in charges and electrical losses associated with transmission and distribution.

Co-location also improves the economics of electricity storage, where lower cost grid power, excess renewables power or power supplied at voltages above equipment specifications can be stored for later use and for sale to the grid at high premium prices as part of the maturing capacity market. Excess heat can also be stored for later use in whatever process needs it. Storage is an indirect efficiency measure, retaining most of what would otherwise have been lost, though it incurs some losses itself.

3.1.3.2. Energy conversion infrastructure.
For mechanical transformations of process materials and moving their mass, energy converters include drivetrains for machinery, comprising motors, drives and power quality devices; hydraulic and pneumatic systems; steam generators; heat exchangers and compressors for chillers and heat pumps.

For this resource, the main benefits of co-location have already been realised in the energy generation and supply infrastructure. In principle, loads totalling up to about 150 kW should be supported from a single motor, since motor efficiency increases up to this level. Provided the transmission losses are less than the efficiency gain from the more powerful motor, sharing the motor for different loads would reduce energy consumption. Consumption would also be reduced through a reduction in part-loading and in any idling time.

In most cases, however, this 'in principle' argument is trumped by very practical considerations such as constraints of physical layout and the acceptable proximity of non-food processes to food processes.

Equipment sharing opportunities are greater where equipment is not 100% utilised.

3.1.4. Energy synergies – overall picture

A benefit of further research would be to generate an expanded pinch analysis that sets out all the main F&D manufacturing processes and all the potentially viable LC biorefining processes, and places them into bands or levels of enthalpy and entropy that would encompass the main thermodynamic variables (Section 3.1.2) in addition to temperature levels and gradients. This could act as a general tool for approximately matching up processes and prioritising the exploration of potential synergies, as part of the methodology set out by Woolley et al. (2018). If useful, this could be extended to all the potentially viable pathways for LC biorefining processes related to their main end products, although it would probably involve a prohibitive amount of data. Data is being generated incrementally, as LC biorefining research is proceeding by focusing on specific conversions for specific products. An example is the list in A10.2 of the EU's 2017 Review of its 2012 Bioeconomy Strategy (European Commission, 2017).

For thermal energy, we have suggested that there could be a circularity in the exchange of spare energy, as shown in Fig. 4 above. This would mean that thermal storage would be an important technical asset in a co-located integrated system. For non-thermal energy – in practice electrical – the synergies and benefits of co-location are realised in the generation, supply and storage infrastructure and the associated market-related dynamics.

3.2. Other resource synergies

Relevant product and process resources in both F&D and precision LC biorefining are ingredients, by-products, energy, water and process agents. The main shareable non-energy resources are:

- Labour
- Water and water supply, treatment and discharge infrastructure
- Transportation space for lower volume ingredients
- Process agents, particularly enzymes
- Intermediate and final outputs from biorefining (chemicals, materials, foods, fuels)
- Probably some sharing of food contact equipment at the front end (initial processing)

The general hypothesis is set out in Fig. 5.

Ingredients would come as various forms of biomass and/or unavoidable food waste from the co-located plant. So,
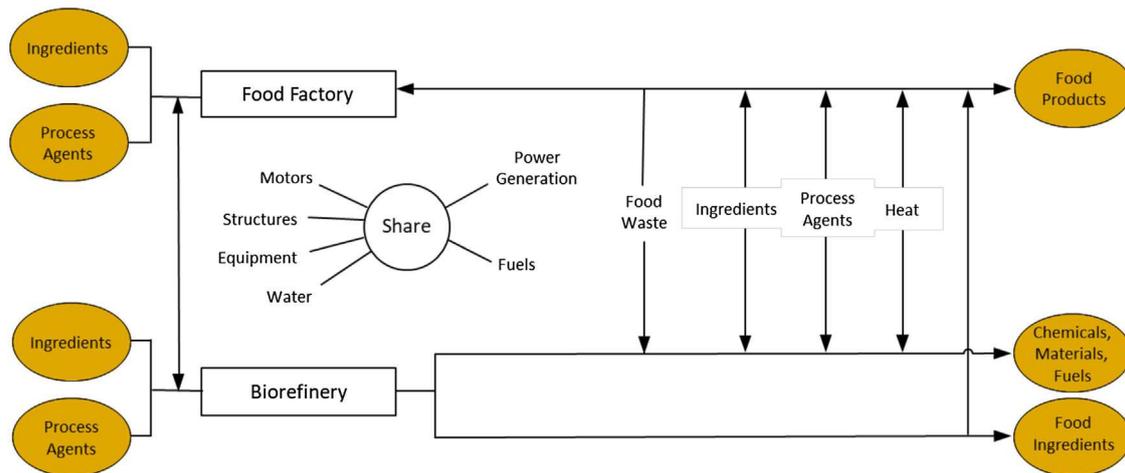
Fig. 5 – Potential resource synergies in co-location of F&D manufacturing with LC biorefining. Previously published in: *Cereal Foods World*, **Vol. 64, No. 4, DOI:** 10.1094/CFW-64-4-0038, **2019, AACC International, St. Paul, MN.**

formally expressed, the case is based on what the biorefinery can offer the food factory, in terms of food ingredients from LC biomass, by-products as ingredients, other resources (including energy,) and infrastructure, and what the food factory can offer in terms of by-products as feedstocks, other resources (including energy), and infrastructure.

How resources (other than those in Section 3.1) could be shared by co-locating operations are briefly elaborated in the following sections.

3.2.1. Labour
Where tasks in one of the two processes can be interleaved in time with tasks in the other process, and skill levels are similar, savings in labour can be made. We can subdivide these into operators, experts and support staff.

If, as is often the case, the processes both use advanced technologies requiring expert skill levels, only one expert would be needed to cover the technologies in both processes.

3.2.2. Water and water supply, treatment and discharge infrastructure
Water is used copiously in both F&D and LC processes. In biorefining its main use is as a process agent, so nearly all of it is repeatedly recycled. F&D manufacturing uses water as an ingredient and for washing and cleaning, but does only a limited amount of recycling because purity and safety are much bigger issues than in biorefining.

Water saving is the most commonly reported benefit in the industrial symbiosis literature (Boix et al., 2015). In addition, water recycling in biorefining requires infrastructure that F&D manufacturing could also use. This sharing would reduce water costs and provide opportunities for savings that might otherwise not have been available; water pinch analysis has greater technical and economic scope where there are more streams of supply and demand between processes. The availability of water recycling infrastructure could also stimulate innovation in on-site treatment in the food industry, to enable recycled water of the same quality as mains water, thereby enabling considerable cost reductions.

3.2.3. Transportation space for lower volume ingredients
Food ingredients are needed in unequal quantities. Therefore, within shelf life, a food product manufacturer either has to store ingredients with higher quantities or order the lower

quantity ingredients more frequently than the higher quantity ingredients. Delivering non-food-product inputs with the lower quantity ingredients could lower their costs of transportation and provide a reason to avoid storage of higher quantity ingredients. Life Cycle Assessments would be needed to establish which arrangement is environmentally better.

Alternatively, truck-full quantities of lower quantity ingredients could be delivered, with the extra being used for non-food products of the co-located biorefinery. The benefits would be either (a) less frequent delivery of lower quantity ingredients and/or (b) higher end-product value associated with each delivery of such ingredients, therefore lower cost as a percentage of revenue.

3.2.4. Process agents, particularly enzymes
Both food and mature LC biorefining use enzymes. Co-location could be used to stimulate the novel use of enzymes in the other industry, or the co-development of new enzymes for functions needed but not satisfactorily fulfilled in either industry.

Alcohols are an example of a class of process agent that the LC biorefinery could provide to the F&D manufacturing plant. Food grade alcohols can be used under several food product use-codes in US regulations (Government Publishing Office (US), 2019). Applications referred to by suppliers include a processing aid in the production of chocolate, confectionery and vinegar and as a solvent for colourings, aromas and flavours (Cargill, 2019; ePURE aisbl, 2019). The work of Campbell and co-workers highlights the use of ethanol as an in-process working fluid to wash feedstocks and precipitate arabinoxylans (Du et al., 2009; Misailidis et al., 2009; Campbell et al., 2019), with ethanol pinch analysis deployed to minimise ethanol usage (Martinez-Hernandez et al., 2013, 2018). Although this work was within a biorefinery, the concepts can extend to a co-located food facility employing alcohols as process agents.

3.2.5. Intermediate and final outputs from biorefining (chemicals, materials, foods, fuels)
There is a significant quantity of protein in many LC feedstocks, not least leaves (Sari, 2015). A good example is alfalfa, often grown for animal feed. Improved techniques for extracting and processing proteins from leaves enable this protein also to be used for human consumption. In the US, alfalfa had

Table 2 – Some edible biorefinery products useful in F&D manufacturing.		
Compound/Product	Source	Reference
Arabinoxylans and xylooligosaccharides (XOS)	Cereal bran, sugarcane bagasse, hemp	Martinez-Hernandez et al. (2018); G. M. Campbell et al. (2019); ISANATUR; LIGNOFOOD Consortium (2016)
Glutamic acid (particularly poly-γ-glutamic acid (γ-PGA))	Corncob fibres	Zhu et al. (2014)
ε-polylysine (ε-PL)	Any LC	Isikgor and Becer (2015)
Lactic acid	Any LC	US20140377821A1 (2014)
Citric acid	Glucose from any LC + reactant	Isikgor and Becer (2015)
Microcrystalline cellulose (MCC) - SenseFi®	Wood	Borregaard https://www.borregaard.com
Fumaric acid	Glucose from any LC + reactant; starch	Martin-Dominguez et al. (2018)
Omega-3 and -6 fatty acids (lipids)	Single cell oils (microbial lipids) using various LC materials	Santek et al. (2018)
Sweeterra™ glucose – proprietary low glycemic index syrup	LC material "such as wheat straw and corn stalks."	Comet Biorefining, Inc (2019)

a higher protein yield (0.90–1.5 tonnes per hectare) than soya (0.96 tonnes) over a 5 year period prior to 2012 (Bals et al., 2012).

F&D manufacturing by-products are another rich source of proteins. F&D manufacturing plants are not set up to fractionate the by-products, but co-location of a biorefinery would enable this as well as the return of by-product constituents to the food plant for inclusion in products. Mirabella et al. (2014) have assembled the most comprehensive information on this to date.

Proteins and their amino acid components can also be manufactured directly from LC material, using biocatalyst molecules or whole cell catalysts. The material is metabolised into sugars and these molecules are then used to build amino acids and protein molecules (Leuchtenberger et al., 2005, focusing on synthesis; Ajila et al., 2012, covering biotechnological methods). Although the same products can be made with sugar crops as the substrate, using LC material extends land productivity and enhances the value of the crop, where there is a market.

The use of LC materials as a source of protein is supported by a recent commercially funded project in the Netherlands, showing that proteins do not necessarily have to be purified to maintain their functionality. The researchers found that proteins extracted from potatoes, blood plasma and peas retained their functionality even in less pure forms, and sometimes their functionality was improved (Meinders, 2017). This result adds to the commercial potential of LC biorefineries and the synergies with F&D manufacturing.

A major element of the thesis of Campbell and co-workers is that biorefineries could create new functional food ingredients not currently available, made commercially viable through the integration opportunities that arise within biorefineries (Martinez-Hernandez et al., 2018). Their work has focussed on a new class of fibre ingredients based on arabinoxylans, but the idea of novel ingredients made affordable via biorefineries is also relevant to some of these functional proteins, and to low concentration, high value products such as functional lipids and surfactants.

Some specific edible products and food processing agents available from lignocellulose are listed in Table 2.

The potential materials and chemicals outputs of a biorefinery that could be used in co-located F&D manufacturing activities are numerous, requiring separate research. They include materials for packaging, a major element of food production that is coming under increasing scrutiny with respect to sustainability, particularly in relation to plastics.

An economic advantage of the synergy of co-location would be that food manufacturers would be able to source more of their ingredients on-site, displacing some supply from upstream processors of agricultural commodities or from specialist ingredients manufacturers. It would be possible to generate a mass index for the co-located site, a ratio of input to output, perhaps also related to value, which would be more favourable than the sum of the separate sites.

3.2.6. Sharing of food contact equipment at the front end (initial processing)

An important reason to share equipment is the seasonal nature of some feedstocks for both food and biorefining, as highlighted by Giuliano et al. (2016). Sharing avoids having to oversize equipment for the biggest input quantity, and is another reason for co-locating food manufacture and biorefining, with food helping out the biorefinery business case.

Subject to official advice (which could be sought from national Food Standards Agencies), the following biorefinery feedstocks used advantageously in food processing equipment would carry low risk, and would allow easy cleaning of equipment following use and prior to use for food production. In many cases, the feedstock would be unavoidable by-product from the co-located F&D manufacturing, particularly where whole crops are brought to the site rather than being separated on the farm or routed separately from the farm:

- Straw
- Wood, including prunings
- Grass/hay
- Leaves
- Fruits – peel, stalks, cores, seeds
- Vegetables – peel, stalks, cores, seeds
- Nuts & seeds – oils, shells, skins, nibs

3.2.7. Infrastructure and equipment at the back end (post production)

There is also considerable scope for sharing of warehouse space and equipment, including the logistics interface. This may be constrained by food safety requirements or considerations, but for packaged goods – food and non-food – these issues can be managed effectively.

Other advantages of co-location

- Lower investment risk due to enhanced risk mitigation factors, making attracting finance easier and cheaper.
- If the biorefinery size is limited by the size of the food operation, it can be designed to produce small quantities of higher value outputs, whilst if it is not limited, outputs can be selected to maximise price against the volume. A co-located biorefinery could enable a food operation to be larger than it would be on its own, thereby enabling economies of scale and lower unit costs.
- Modular design and investment in both industries increases flexibility and resilience and reduces risk, compared to the same for either industry alone. This extends the principle introduced by the multinational Mondelez with its 'Line of the Future' (Mondelez International, 2015 and personal communication, Mondelez Engineering & Energy Manager, March 2017).

3.3. *Whole system synergies*

At this point it is instructive to stand back and consider an even wider perspective than that discussed so far. Biomimetics, also known as biomimicry, is one fertile approach to this, particularly since we are dealing with biological resources and systems. Biomimetics is now a mainstream problem-solving approach in engineering, in which inspiration is gained from the engineering principles that support life on earth, many of which human technology has not yet emulated (Speck et al., 2017; Harman, 2013).

Biological conversions in biorefineries use a range of enzymatic and microbial species that degrade LC material in the natural environment. A major sub-environment for such processes is animal digestion, which has evolved to process the entire spectrum of biological materials at body temperatures and pressures, so does it provide any partial or complete blueprint for the synergistic operation of F&D manufacturing and biorefining?

In animal physiology, the energy used to process material (e.g. in the metabolism of gut bacteria, muscle movement) as well as energy used in supporting processes (e.g. for the heart muscle) is integrated into the one overall physiological system that delivers energy, materials and process molecules from the same inputs to power the process, make structures and enable critical reactions. Even the waste products deposited outside the body, and the molecules that carry waste heat from the body, become useful for future cycles of resource production. This proven model encourages the design of food manufacture and biorefining processes to be intimately related.

One way to implement such intimately synergistic design would be for a biorefinery to take as feedstock whole unseparated plant materials – edible and inedible – and process them much as an animal digestive system would, with appropriate modifications. One change would be the treatment of fibre. In most animals, whether ruminant or not, and including mammals, the fibre of lignocellulosic material, from the micro-scale of cell walls to the macro-scale of skin of fruit or, for some, the bark of a tree, is an essential aid to successful digestion as well as to maintenance of gut health (as research on human diet is increasingly telling us, for example). In the biorefinery, this is not a necessary function, so could be separated earlier than in digestion. Dietary fibre from LC sources that are not directly edible can be added back into food products.

LC biorefining research already investigates animal digestive enzymes and bacteria as potential process agents. Examples are lytic polysaccharide monooxygenases used by the insect *Thermobia domestica*, facilitation of cellulase action by hemocyanin in marine crustacean woodborers of the genus *Limnoria*, and the mimicry of ruminant digestion (Agematu et al., 2017; Weimer et al., 2009).

The main resource efficiency benefits of this intimately synergistic design approach would be:

- Avoided costs of separating edible from inedible parts of the feedstock on the farm or at the initial processing facility.
- Extension of food resources, through extraction of food products and product components from the lignocellulosic material:
- Table 2 above gives examples of proteins available from LC material.
- The peel and skin of fruits and vegetables contain many compounds and structures used in animal physiology which humans lose by discarding the material rather than processing it outside the body to enable it to be consumed (O'Shea et al., 2012; Kowalska et al., 2017).
- Use of the heat applied in food processing – aimed at increasing the aesthetic and sensory pleasure of food (e.g. baking, toasting) – for biorefinery processes, which carry a higher energy hurdle than food processing (as discussed above).
- The manufacture of process agents, particularly enzymes, from a small proportion of the input material.
- The use of part of the processed material for energy.
- With biological processing, a minority of the material is converted to gases, which can be used for process energy. (This improves on animal physiology, in which these greenhouse gases are vented to atmosphere.)

The animal digestion model is too complex to be explored in the present paper, but is a subject for further research on the synergy concept proposed here.

Having set out the theoretical basis for our co-location thesis in Section 3, we now move to answer the research questions posed in the Introduction: Does this proposition (synergies providing commercial and environmental benefits) hold true for selected types of food products as case studies? And what are the projected financial benefits?

4. Methodology

Coffee production is an example of a food process in which thermal processing and production of a waste stream are prominent features (Schwartzberg, 2013; Kovalcik et al., 2018). Roasting of coffee beans and processing of spent coffee grounds were therefore selected as the case study processes. The following steps were taken:

1 Define production processes, using published information.
2 Add energy and mass balances from the same sources, through calculation if the data is not stated.
3 Identify energy- and materials-sharing opportunities, using the structure illustrated in Fig. 5, and evaluate in terms of quantity, quality and net environmental effect.
4 Attach economic values to the resources and the processes in order to determine the commercial benefits or disbenefits of co-location.
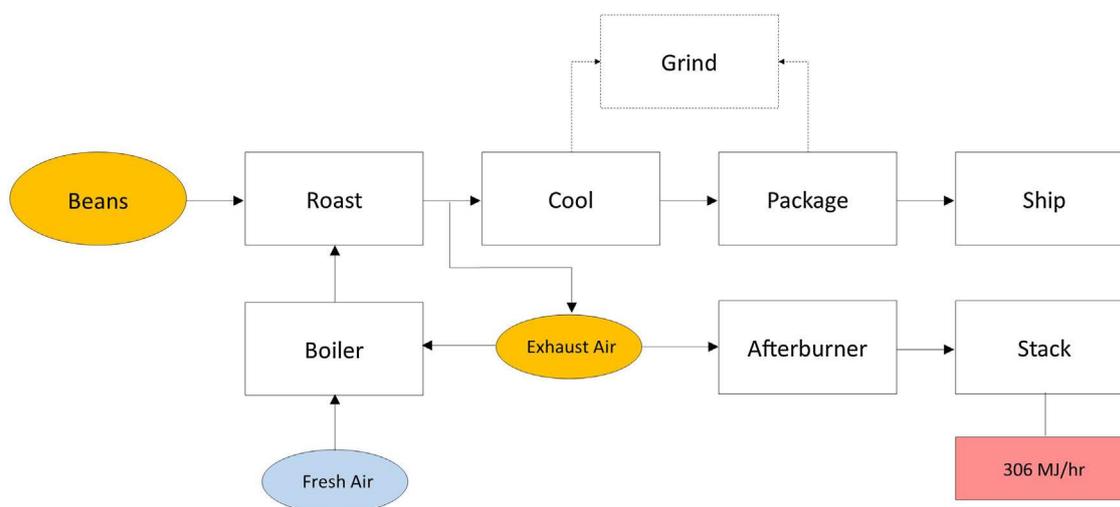
Fig. 6 – Schematic of a typical coffee roasting process.

Sources: (Pantaleo et al., 2017[5]; Schwartzberg, 2013).

4.1. Coffee roasting and spent coffee grounds

Coffee roasting was selected as an exemplar F&D manufacturing process because the valorisation of spent coffee grounds (SCG) has received much research attention (e.g. Kovalcik et al., 2018) and some commercial implementation, but the benefits of co-location with coffee roasting have not been explored, and the valorisation of SCG has not been fully optimised in the applications developed to date.

4.1.1. Production process

Fig. 6 schematically shows a typical medium/large scale coffee roasting process.

Dried green beans (moisture content 11 wt%) enter one or more rotating chambers at a total rate of 500 kg per hour and are heated with hot air up to a temperature range of 180 °C to 220 °C over 10–20 minutes, and then rapidly cooled. Where ground or instant coffee is the final product, the cooled beans are ground to various grades. Some of the exhaust air from the roasting chamber is circulated to preheat the incoming fuel (usually gas) to the boiler up to the point when target temperatures are reached; the rest of the exhaust air then passes through an afterburner with a separate fuel supply which carbonises the volatile organic compounds and ash to prevent air pollution. Afterburners can use a catalytic membrane to capture significant proportions of entrained pollutants or simply use the thermal energy at a sufficiently high temperature to perform the entire pollutant-reducing function.

The process is fully characterised mathematically in the main source paper (Schwartzberg, 2013).

SCG is the solid residues of the extraction of coffee chemicals via brewing and subsequent filtration. Commercially, these arise from high street retail cafes, restaurants and food service outlets and from the manufacture of instant coffee which would involve the optional grinding process in Fig. 6.

4.1.2. Biorefining

Like petro-refining, the full value of biorefining is realised once the full set of viable outputs has been produced. The scale involved is beyond the resources and scope of this study, so

the co-located biorefining system boundary was drawn around the pretreatment stage plus some easily available products, as shown in Fig. 7.

The pretreatment process shown in Fig. 7 is ionoSolv, a patent-pending system developed at Imperial College London (Brandt-Talbot et al., 2017). ionoSolv uses the ionic liquid triethylammonium hydrogen sulfate ([TEA][HSO4], CAS 54272-29-6) for the first time in LC biorefining, which enables a cost reduction of at least half against other solvents, including 1-ethyl-3-methylimidazolium acetate, the most researched ionic liquid in this space. ionoSolv has been demonstrated at lab scale (using miscanthus) and there are strong technical and economic reasons for confidence in its similar viability at pilot and full scale (Brandt-Talbot et al., 2017[1]). It is being commercialised as *BioFlex* through Chrysalix Technologies Ltd. ionoSolv is based on the assessment that it is more efficient to separate the lignin, hemicellulose and cellulose before any other processing of the LC material (the so-called 'Lignin First' approach). A later paper (Gschwend et al., 2018) has improved on the process modelled in the present paper, which uses Brandt-Talbot et al. (2017) and Hallett et al. (2014).

Other leading edge pretreatment technologies could be modelled, from the categories outlined in Section 1. Energy balances would be different in each case, and would need to be separately modelled.

As shown in Fig. 7, the ionoSolv stage begins with dissolution of the LC feedstock (SCG plus silverskin, the skin or husk of the bean) in a ratio of 1:8:2 feedstock: [TEA][HSO4]:water. The optimum residence time is 4 h, so a 16 -h day of 4 cycles has been modelled. (Alternatively, this could be four vessels of 125 kg (plus 6̃ kg silverskin).) We then start to meld ionoSolv with our own extractions, firstly separating out proteins from a solids residue of cellulose-rich material (CRM) and remaining liquor whose main constituents are hemicelluloses and lignin. The CRM is then washed before we divert from ionoSolv to precipitate carboxymethylcellulose (CMC), a widely used agent and ingredient. A residue of CRM is left, which has an economic value, and liquor. Meanwhile, we then precipitate more CMC from both batches of the liquor and, following ionoSolv, at least 90% of the [TEA][HSO4] ionic liquid is recovered. (If ethanol were the post-pretreatment solvent instead of

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[5] This source also uses secondary information for the reference coffee roasting process.

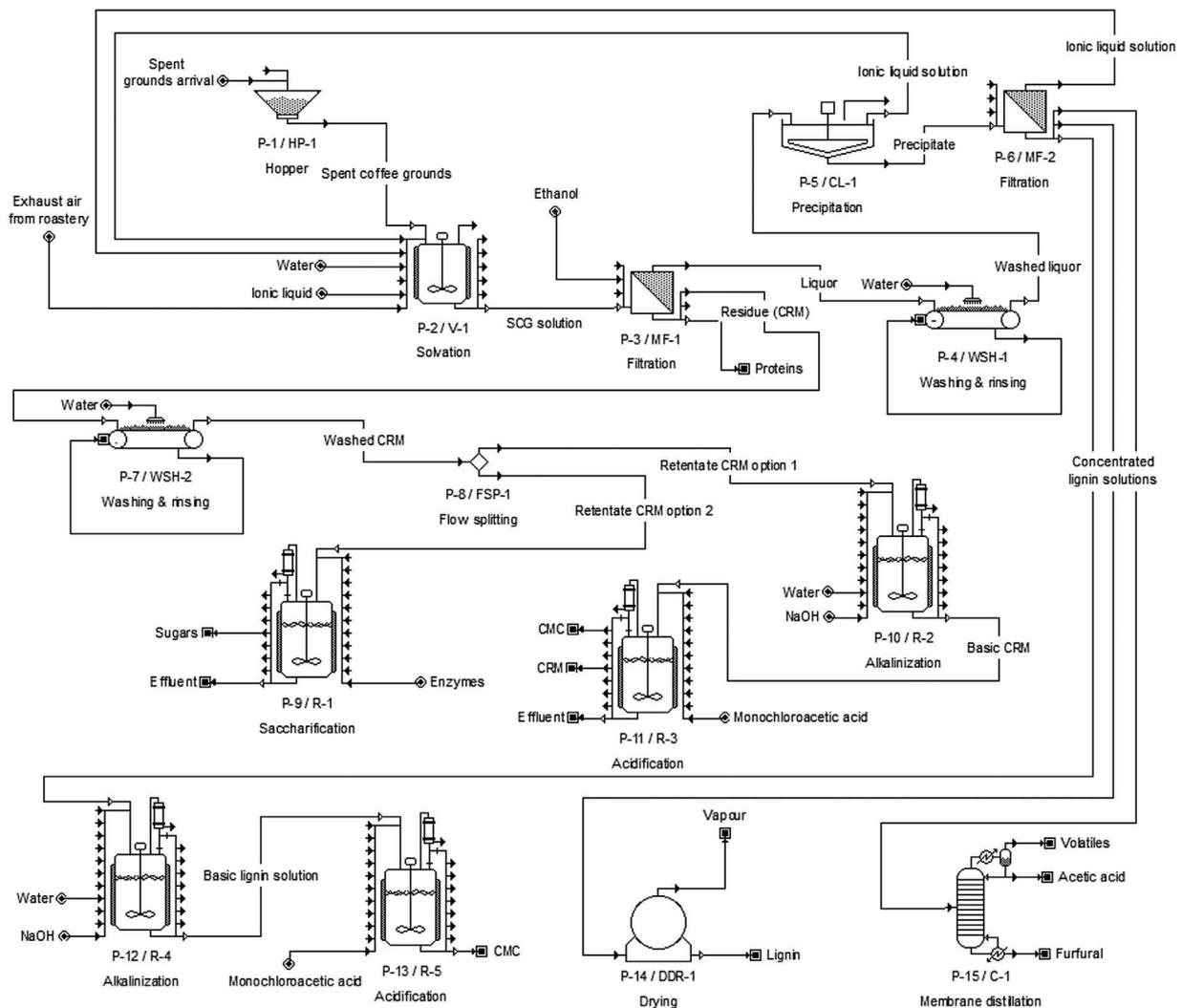[1] Also personal communication, Dr Agi Brandt-Talbot, February 2018.

Fig. 7 – Ionosolv pretreatment process plus simple products from SCG, receiving heat from coffee bean roasting.

water, the recovery rate could be at the 99% level reported by Brandt-Talbot et al. (2017), but would require additional heat.) From the balance of the liquor, the lignin is precipitated and dried, and furfural, acetic acid, volatiles and remaining solids are filtered and distilled. The research underpinning ionoSolv reports that at least 100 cycles of IL recycling are possible (Brandt-Talbot et al., 2017[2]).

5. Results and discussion

5.1. Coffee roasting and spent coffee grounds

Fig. 8 shows how the coffee roasting process could be modified if LC biorefinery pretreatment was located on the same site.

Exhaust air from the roasting chamber is still recycled back to the boiler. The balance of hot air is sent straight to the biorefinery and the afterburner is eliminated, because the Volatile Organic Compounds (VOCs) and ash particles can be processed in the biorefinery.

5.2. Resource sharing

We now inventory the resources which could be shared in this co-location. This is shown in Fig. 9. We use the same list of resources as the generic synergies described in section 3.

5.2.1. Energy
5.2.1.1. *Heat.* The net output to the biorefinery is 256 MJ per hour, calculated from data in Schwartzberg (2013).[3] This is 49% of the total enthalpy for coffee roasting in the *co-located* reference case above.

Critically, we assume that, with effective pipe layout and insulation, the recycled liquids used in the biorefinery retain 90% of their enthalpy for the next cycle of use. This means that, after the initial heat input to the solvation vessel of 9108 MJ for the first cycle of four hours (or four vessels over one hour), the three subsequent cycles of four hours each day require external input of 2732 MJ. Since the other two heat loads are at a lower temperature than solvation, we assume a heat input of 10% of the load in each case for each cycle. The roaster stack enthalpy overall is only 7% of the refinery requirement. Its temperature is more than double that specified for

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[2] Also personal communication, Dr Agi Brandt-Talbot, February 2018.

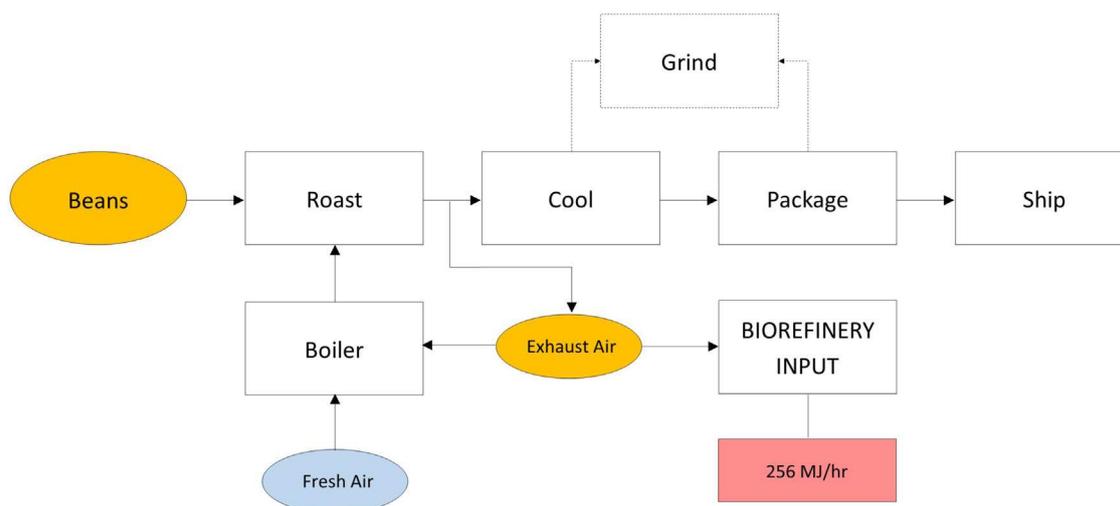[3] Calculations available in the Supplementary Information.

Fig. 8 – Schematic of modified coffee roasting process linked to downstream biorefining.
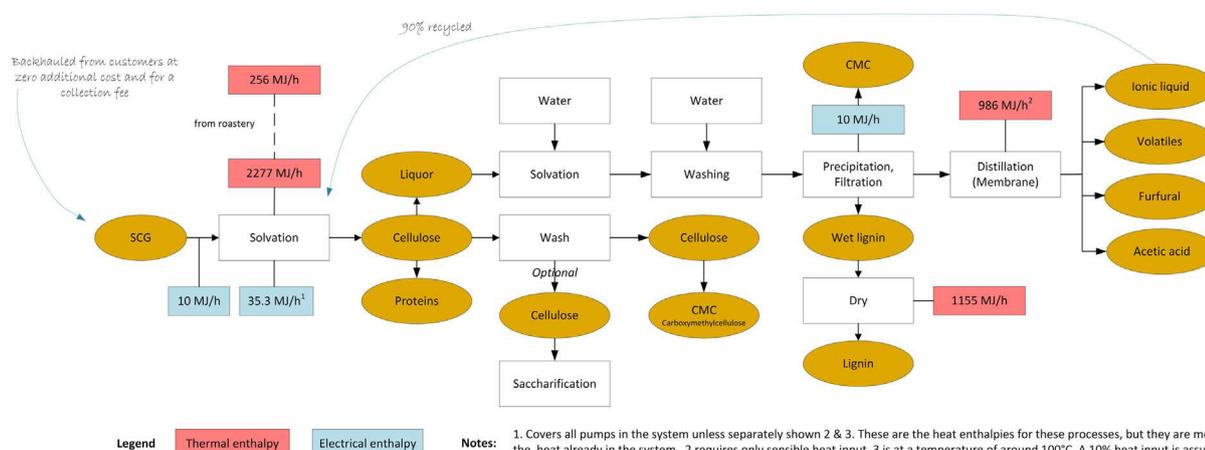

Fig. 9 – Energy and other resource synergies in coffee roasting and SCG biorefining.

ionoSolv pretreatment, the only process in the biorefinery at an elevated temperature. Losses in the transfer of heat from roaster to refinery pretreatment would be negligible because heat transfer to the solvation vessel would be a direct air-to-air exchange involving diffusion and bulk motion.

5.2.1.2. *Energy generation and supply infrastructure.* We suggested in Section 3.1.3.1 that a greater concentration of electricity use through co-location would make on-site generation more viable. Certainly the power requirements of the roastery and the biorefinery are mutually supportive in this respect, with the roastery needs being 39% of the biorefinery input. Processes with a heat requirement should initiate consideration of a combined heat & power (CHP) system. CHP is normally heat-led and needs at least 5000 h of heat load for viability. The co-located processes together need heat input for 5600 h.

In this case, the roaster is providing only 7% of the biorefinery's heat requirement, so the balance of loads is 18% electrical and 82% heat. Where the CHP capacity is set to meet the peak heat load of the combined site, the heat provided is 2.4 times the net heat load of the combined site, and the electricity generated is a multiple of 8.4 above the annual combined load. If the CHP were to be sized for peak electrical output, the heat generated would only meet 36% of the annual net heat load of the site.

An interim design is possible, with the CHP sized somewhat above the peak electrical load such that electrically-based heat could top up the CHP heat, perhaps with heat pumps, but this level of detail goes beyond the scope of this paper and we have not modelled it. We conclude in this case that the low heat contribution from the roastery to the biorefinery makes the technical and business case for CHP more complex than a case where the waste heat and the biorefinery loads were more closely matched.

For other cases, there is useful information to guide consideration of CHP for co-location. A study for BEIS in 2013 assessed the technical and commercial potential for CHP in the UK up to 2030 (Ricardo, 2013). The study set out capital cost factors for CHP by size of plant and type of energy conversion technology, based on actual commercial values. Using the factor for a small-scale natural gas reciprocating engine (<1 MWe) would put the capital cost of a small CHP system at our co-located site, if it were needed, at £184k. The Ricardo AEA factor estimate needs to be updated for UK producer price inflation 2013-19 of 8.9% (Office for National Statistics, 2019), increasing the CHP capex at the co-located plant we have modelled to £200k.

If the biorefinery were to extend to additional refining beyond the outputs modelled here, then the case for CHP is likely to strengthen. Chemicals and oil refineries are by far the two biggest users of the UK's CHP capacity (33% and 32% respectively, in 2012 – Carbon

Trust, 2012), and this fits exactly with the co-location approach.

The alternative to CHP as a benefit of co-location in this case is separate energy sources of power and heat, whether on- or off-site. An emerging option is heat pumps. Given a power to heat ratio of 1.2 for small scale CHP (Ricardo, 2013), a coefficient of performance of at least 3.4 would be needed to compete with CHP on efficiency.

5.2.1.3. *Energy conversion infrastructure.* The power requirement of the reference roaster is made up of relatively small motor loads, such as for rotating the roasting chamber, the chiller, various mixers and fans, and conveyors.

In Section 3.1.3.2 we suggested that, in principle, motor efficiency could be improved by using bigger motors for multiple loads, up to an aggregate 150 kW. Roaster design is often compact to minimise heat losses over pipe lengths. Configurations might include using vertical space, for example with the roasting chamber and a large motor at floor level and other equipment above, acquiring convected heat and using a vertical transmission from the motor. Such consolidation of motor power is very unlikely to be possible for the biorefinery.

A greater volume requirement for insulation across the co-located site should enable savings in capex through lower bulk prices.

5.2.2. *Non-energy resources*

5.2.2.1. *Labour.* The roastery is a batch process, but it operates batches continuously for six hours per day. The solvation stage of the biorefinery involves residence times of four hours but could use four vessels to maintain production per hour. Since both coffee roasting at this medium scale and biorefining can be largely automated, with appropriate sensing, or settings programmed, it should be possible to schedule processes so that operating staff can divide their time between the two processes.

Where roasting is not automated or programmed, it might be argued that coffee roasting requires a skilled artisan, whilst the process management involved in the biorefining requires less skill.

5.2.2.2. *Structures and equipment.* Apart from motors, there are no opportunities for sharing of production structures or equipment in this case, although for other co-location cases such sharing is more likely.

For a new site, production buildings and administrative buildings can be shared.

5.2.2.3. *Feedstock shipping.* Roasted coffee beans, where not further processed on-site (e.g. into instant coffee), are delivered to customers directly, by contracted couriers or via distributors for on-site bean-to-cup services in foodservice outlets (high street cafes and catering operations). All these customers generate SCG. With appropriate receptacles for passive drying, occupying the same space as the roasted coffee beans they once were, the SCG can be collected by the same vehicle delivering a new batch of beans and backhauled along the same distribution routes to the roastery site, at very low additional cost. Most of the customers are likely to be paying for disposal of their SCG. The roaster can undercut this charge because it would represent a new source of income and, in the case of direct distribution, the roaster would incur only very low additional costs in backhauling. The opportunity for the coffee distribution network to become also the collection network, at negligible additional cost, only arises because of the co-location, so that the SCG are delivered back to the same site, but to the biorefinery side of it. As collection of waste is a significant barrier to this sort of reuse, a significant benefit of the co-location scenario is to eliminate that barrier.

Co-location of the biorefinery with instant coffee manufacturing would enable the SCG to be processed on the same site, again with virtually no collection, transport or feedstock costs.

By contrast, a standalone biorefinery would incur the shipping costs of both feedstock and of those outputs that in the co-located scenario are used by the food plant.

5.2.2.4. *Water and water supply, treatment and discharge infrastructure.* The roastery uses water only for quenching (an insignificant quantity) and for cleaning. In our model (not shown in Fig. 8), 5̄0 kg of water per hour are released from the green beans as they roast, reducing from a delivered content of around 11% to 1%.

At the solvation stage of the biorefinery, 218 kg of water are added to the SCG and ionic liquid (IL) mix, so if the 50 kg of vapour from roasting could be collected this would comprise 23%. Recycling and treatment (as necessary) of the process water means, however, that the net water consumption of the biorefinery should be small.

5.2.2.5. *Shipping space for lower volume ingredients.* This case does not offer an opportunity for this synergy.

5.2.2.6. *Process agents, particularly enzymes.* This case does not offer an opportunity for this synergy, because coffee roasting does not involve any process agents.

5.2.2.7. *Intermediate and final outputs from biorefining (chemicals, materials, foods, fuels).* The outputs from the biorefinery are shown in Fig. 9 below.

Table 3 lists these outputs and their functions as modelled. The final column states the options available if the co-located biorefinery could be designed to be capable of tuning its processes and outputs to market conditions.

Kovalcik, Obruca, & Marova (2018) have produced an excellent review of the potential products from SCG valorisation. As always, a number of conditions need to be in place for the further fractionation of outputs to carry a sufficiently strong business case. These include:

- Sufficient quantity of output for commercial viability.
- Development of optimum reaction pathways, along with development of lower cost processes, for example cheaper catalyst materials, specific synthetic microbes, and cheaper or more efficient separation processes where separation is currently difficult. Food co-location may be able to help here.
- Catalysts may need preheating, for example zeolites (Sixta, 2017).
- Scheduling and enterprise-wide optimisation strategies.

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[6] There is increasing evidence that CMC (also called cellulose gum) is a contributory cause of inflammatory bowel diseases (Martino et al., 2017).

[7] Lignin is a heterogeneous polymer and its composition varies according to feedstock. The analysis in Table 3 covers lignin from both SCG and any other type of LC feedstock that the biorefinery may flexibly source. The latter would of course produce higher quantities.

Output	Quantity (tonnes/y)	Functions (not exhaustive) As produced in model	If further fractionated
Table 3 – Outputs from the modelled biorefinery and options for enhanced valorisation.			
Proteins	126	Structural component of plants and bodies and muscle component Many functions in food products and processes (could be supplied to co-located food operation for incorporation into their products).	Roles in plant & body metabolism, immune & hormonal system, cell function & reproduction.
CMC (carboxymethyl cellulose), food grade	224	Thickener & emulsifier in food (E466) and non-food products.[6]	–
Cellulose pulp	130.5	Many functions	Many functions
Lignin[7]	78	Fuel	As macromolecule: carbon fibre, dispersant, binder/adhesive, flotation agent, emulsifier, stabiliser, agent for grinding, electrolytic refining and tanning, inhibitor, protein precipitant, flame retardant At micro to nanoscale: surfactant, reinforcement, carrier, anti-oxidant, biocide, UV blocker
Furfural	105	Binder, solvent	>30 chemicals with current and shorter term potential application (Mariscal et al., 2016). Applications include elastic fibres, PET, PEF (polyethylene furanoate), process chemicals.[a]
Acetic acid	37	Chemical reagent, fungicide, counterirritant, solvent, flavour, colour, preservative, bleaching. Primary application is in the food industry (Baumann and Westermann, 2016).	PET, inks, paints, coatings (Baumann and Westermann, 2016)
Solids	64	Fuel	Potentially many, depending on content

[a] Some functions can involve high costs due to batch processing and high pressures. Mariscal et al. (2016) survey better processes being developed.

The previously reported problem of low yield from standalone biorefineries with furfural as a main output (Bozell and Petersen, 2010; Brandt-Talbot et al., 2017; Eseyin and Steele, 2015) is overcome in our scenario because it is a by-product. This helps avoid significant capital expenditure. Also avoided, for the same reason, is the need to control the variability in the biomass feedstock properties which a dedicated furfural biorefinery ideally needs in order to reduce processing steps.

Developments in LC biorefining technologies may support innovation or lower costs in food processing. For example, electrochemical hydrogenation of furfural is advantageous because hydrogen is generated in situ in the reaction cell, thus saving a lot of cost. This use of electrochemistry could then enable its use in other processes for food production – though not for hydrogenation, for health reasons. This would be particularly advantageous if the electrochemistry were solar-driven. Electrochemical hydrogenation would also produce oxygen which could be used in either production process as appropriate.

Roasted coffee has one of the highest concentrations of furans (furfural, 5-methylfurfural, furfuryl alcohol, furfuryl acetate) among food products (Eseyin and Steele, 2015). These VOCs represent an input to the biorefinery (as well as an output), so the furfural yield in the process modelled here is likely to be higher than that obtained from other LC sources.

In addition, if taken to a detailed specification stage, the model would also include the small proportion of the SCG and silverskin feedstock comprising fat and ash, as well as VOCs and ash from the coffee roasting.

It can be seen that there is significant further value that could be extracted. Proteins, CMC, cellulose, furfural (in lim-

ited quantities) and acetic acid can be used as food products or process agents, extending the source from edible feedstocks to SCG lignocellulose, in practice (although not technically) a non-food product. Alternatively, sugars can be produced. The same would apply to other non-food LC feedstocks such as straw and animal products such as hair. The highest gain is where the co-located food operation can use or modify these as ingredients, process agents or even food products in their own right, because the costs of inputs would be reduced. The food products that a coffee roaster could also produce with modest investment are:

- Coffee flavours and aromas. Cafés making their own food products are one type of customer which could use these. Capturing aroma is done in the manufacture of some beverages, such as the fruit drink Ribena (Lucozade Ribena Suntory, 2019) and instant coffee (TEC Square Solutions Inc., 2019).
- Low glycemic sugars, where the cellulose-rich material (non-lignin) is fermented rather than processed into CMC, furfural and acetic acid. A subset of café and foodservice customers would also be interested in these, particularly if they cost less than other sources, as a diabetes-control ingredient to replace glucose and sucrose in cakes and similar food products.

The cascading valorisation of SCG sketched here contrasts with the sub-optimal conversion of SCG reported elsewhere, where energy has been the only use and the energy product is apparently sold for only ~$1/kg (2019). It is interesting that the SCG from at least one large instant coffee production site in

Table 4 – Economic values for heat from revised roaster process to pretreatment solvation.

	Separate		Co-located		Saving		
	GJ/y	$/y	GJ/y	$/y	GJ/y	%	$/y
Gas for heat	6123	80,966	5,739	75,887	384	6	5,079

Table 5 – Summary P&L.

Item	Value ($k, rounded)
Operating costs	455
Revenues	966
Profit	511

the UK is used only to supply heat to processes on site (Nestle, 2011).

5.2.2.8. *Food contact equipment at the front end (initial processing).* Although hoppers and their feed conveyors could be shared, this would probably add to the water associated with green coffee beans, because of the water content of SCG, and therefore to the energy used in the roasting chamber to drive it off.

There are no other such equipment-sharing opportunities.

5.2.2.9. *Infrastructure and equipment at the back end (post production).* Since roasted beans are packaged in sacks that could be sealed, and the biorefinery outputs are also likely to be in sealed packages, it should be possible to share warehouse space and equipment, although clearly with the products segregated into areas. The logistics interface would be shared as described above, with vehicles backhauling SCG.

5.3. Economics

An initial assessment of the economics of co-location compared to the reference case was undertaken and is reported below. All the unit values, assumptions and calculations used are in the Supplementary Information.

5.3.1. *Energy: heat*
Table 4 shows the economics of changing the heat features of the roaster and supplying the waste heat to the solvation stage of LC pretreatment on a co-located site. Roaster throughput is 750 tonnes per year of dried beans; biorefinery throughput is 733 tonnes per year of SCG dried to 35% and silverskin. Co-locating the operations leads to a saving of 6% compared with the energy usage of the separate operations.

5.3.2. *All resources*
From our model, the summary annual profit & loss figures for the whole biorefinery part of the co-located site are as shown in Table 5 (details in Supplementary Information).

The Net Present Value (NPV) and the Internal Rate of Return (IRR) depend on the capital cost estimate. There is limited literature on the derivation of capital costs for biorefineries. Within a wider study, Tsagkari et al. (2016) gathered data from 11 commercial implementations of thermochemical lignocellulosic biomass-to-ethanol plants, involving gasification followed by syngas fermentation, to produce a median capex figure of $2,889 (2011 $) per ton (no definition of quantity was given so it is assumed this is a US ton). This figure comprised production site costs (ground preparation and production equipment) and auxiliary equipment costs. If applied to the small co-located biorefinery, the capex would be £2.1 m.

However, a thermochemical plant involves high temperatures and elevated pressure, as well as drying and filtration, so is not comparable with our low temperature processes.

Another source of data is from a commercial contract in which the lead author was involved, and from which the main separations have been taken in the present model. The pretreatment was also similar, involving ethanol hydrolysis. This contract, in 2014, costed the production equipment required, arriving at a total of £96k for a production capacity of 114 dry tonnes per year; $158k in 2014 US dollars. Since that study uses comparable processes to the co-located refinery, this figure is a more reliable basis for estimating capital cost. The following equation is used to convert the estimate from one model to the other:

$$C = C' \times \frac{cap}{cap'} \times 1.5 \qquad (1)$$

where C is the co-location capex, C' is the reference contract's capex, cap and cap' are the capacities in tonnes of the co-location and reference refineries respectively, and 1.5 is a maximum proportion of the production site costs used for estimating auxiliary costs from an authoritative source, the minimum being 1.25 (Peters et al., 2004).

Enumerating the equation produces
158,000 x (733/114) x 1.5 = $1.5m

In addition to production site and auxiliary costs, a commercial project would incur Engineering, Procurement and Contracting (EPC) costs, which include process design, working capital and startup costs. These have not been included here because they are dependent on other factors, mainly the learning rate from a first of a kind (FOAK) implementation and the financial position of the owner or contracting company.

The above estimate is thirteen times the proportionate cost of the ionoSolv case in Brandt-Talbot et al. (2017, Supplementary Information). If a commonly used 0.7 factor was applied to that figure to account for economies of scale, the capital cost of the co-located ionoSolv system modelled here would be $168k.

This logic train through capital cost estimation enables us to produce the figures in Table 6 for the investment value of co-location. These figures incorporate best estimates for labour, overheads and miscellaneous materials costs which were not derived from any particular reference framework. All the details are in the Supplementary Information.

It can be seen that the value of the biorefinery outputs in terms of the profit realised far exceeds the saving from not using the gas for heat. The use of the waste heat is not the only reason for the large increase in net income to the site; that is due to the investment on the site, but this is made easier and more attractive by the synergies we have identified.

On the downside, capital costs would be higher for a commercial implementation to include EPC, working capital and startup costs.

On the upside, all aspects of capital cost would reduce in line with the number of installations and with innovation. In addition, there is scope for additional income from the biorefinery through (a) charging customers for collection of

Table 6 – Net present value and internal rate of return for the co-located biorefinery.					
Item	Value ($k)	NPV ($k, 8%, 5 y)	NPV ($k, 8%, 10 y)	IRR (5 y)	IRR (10 y)
Capex estimate	1,524	629	2,017	35%	49%

SCG (Section 5.2.2); (b) addition of other lignocellulosic feedstocks; and (c) downstream processing into chemical building blocks, intermediate and secondary chemicals, and materials and products, as well as biofuels.

The biorefinery profit is a worthwhile addition to the normal annual income for the roastery of an estimated $18 m for the 500 kg per hour / 750 tonnes per year output of one of the source models for the roastery (Pantaleo et al., 2017). A profit figure has not been estimated due to uncertainty about costs.

Coffee roasting is an unusual case from the F&D manufacturing industry because of its high margins and relatively low costs. Sharing of resources and associated costs would be more significant in most other cases. More generally, while the current case study has illustrated synergies from a very limited interaction, it is clear that a more complex co-located facility would give greater scope for synergies and savings.

Corroborating support for this analysis comes from a recent study of a co-located sugar cane mill and biorefinery processing the sugar cane bagasse (Clauser et al., 2016). (As discussed earlier in the Introduction, co-location related to sugar production is adventitious rather than designed as a replicable template for other foods, and is unusual because of the seasonal nature of sugar refining.) Clauser et al.'s modelling of the small-scale refinery at a sugar bagasse mill, with xylose syrup as an output in one scenario, produced IRRs of 12% for energy generation as the output and 19% for MDF board as an alternative output. Furfural produced an IRR of 16% for MDF. Input was 15,000 t/year of dry bagasse, which seems applicable to co-location with many F&D manufacturing sites.

6.   Conclusions and further development

In this research we began to test the thesis that synergies between F&D manufacturing and fractional biorefining of lignocellulosic materials, together with the value of their outputs, could make co-location of facilities commercially and environmentally attractive. We specifically attempted to address the following key questions:

1 Does this proposition hold true for a selected type of food product as a case study?
2 What are the projected financial benefits?

It is clear that there are several areas of synergy between the two industries that enable the sharing of resources. In general, the respective thermodynamics are asymmetric, allowing for a circular flow of energy between them by design. Flows of materials can similarly a priori be mated upstream, within and downstream of the processing plant, and water within the facility. Such integration enables improved efficiencies of infrastructure investment and deployment, including for logistics.

Within its capacity of 750 tonnes of coffee beans and the other system boundaries described, the overall energy efficiency gain of co-location in our case study, compared to separate operations, is 384 GJ per year, or 6%. This converts into an economic gain of $511k per year for the roaster, with a contribution from the energy savings, but with a much greater

contribution from the value of the biorefinery products. The economic gain is only small in proportional terms due to the current exceptionally high revenue and profit available in coffee roasting. For most other cases the proportional gains would be significantly higher.

Our analysis enables the conclusion that the thesis appears to be valid for the co-location of coffee roasting and SCG valorisation, with attractive financial gains. Environmentally, there would be an energy efficiency gain if this model were implemented (through heat saving and potentially CHP) and, although not quantified, there is little doubt that several other resource efficiency gains could be made.

Looking ahead, the question arises as to the extent to which these gains would also be realised if extended to other food/biorefining combinations, and to a greater scope and complexity of combinations. Addressing the extension of the concept more widely requires formalisation of the integration methodology. In the current analysis, we easily normalised production in both processes by the hour, and there are relatively few energy and other resource integrations. For integration of more than two processes and more integrations, a number of linear and non-linear programming models are available. Two that are used for industrial symbiosis modelling are CPLEX (IBM Corp, 2017) and Total Site Heat Integration Algorithms (Liew et al., 2014). Industrial symbiosis analyses have focused on integration of different operations on separate sites within industrial parks, whereas our approach would use the models to optimise co-location on the same site. Standard process engineering packages can also be used.

The present paper should provide a foundation for further modelling of the ionoSolv process integrated with manufacturing of other food and drink products, including the improved ionoSolv process described by Gschwend, Malaret, Shinde, et al. (2018). As well as creating new knowledge with respect to the combinations involved and the effectiveness of the models, such work should also be commercially useful by generating outline business cases for co-location, thereby having potential for positive environmental and economic impact. It could take the form of a map, along the lines of the Resource Mapping Tool produced in Scotland,[4] which characterises the bioresources available in the country and includes a heat map of protein arisings. The further modelling envisaged would go beyond the Resource Mapping Tool in that it would also include co-location benefits.

An example of this potential is the wet fractionation of cereal bran described in Soukoulis and Aprea (2012), which fits at many stages with the ionoSolv and following processes modelled in this paper. A co-located mill or cereal products manufacturer could therefore have this process carried out in the adjacent biorefinery at no capital cost.

Future modelling could also substitute other pretreatment processes for ionoSolv.

Issues that such assessments need to take into account include:

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4 See www.ibioic.com/what_we_do/scottish_bioresource _mapping_tool/d1142/

- The potential for improvements in the incumbent technology. The coffee roasting process used in this study is the system used by most medium and large scale roasteries. The energy consumption is $\overline{3}82\,kW\,h$ per tonne of roasted beans. The case for co-location would need to be reassessed if a technology such as Revtech's spiral continuous electric roasters could be independently verified for the claimed $140\,kW\,h$ per tonne performance, and it were to take a significant portion of the market (REVTECH Process Systems, 2011).
- Seasonality and long-term variations in energy and feedstock availability.

It is hoped that future modelling based on the present work will attract the attention of both the food and drink industry and the emerging biorefining sector, such that these two sectors, often seen as antagonistic in their competition for biomass resources, can emerge as giving synergistic benefits beyond what either can achieve alone.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.fbp.2019.08.001.

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