EPSRC CENTRE FOR INNOVATIVE MANUFACTURING IN FOOD

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PRINCIPAL INVESTIGATOR: PROF. T. FOSTER, UNIVERSITY OF NOTTINGHAM

CO-PRINCIPAL INVESTIGATORS: PROF. I. NORTON, UNIVERSITY OF BIRMINGHAM AND PROF. S. RAHIMIFARD, LOUGHBOROUGH UNIVERSITY.

EPSRC CENTRE FOR INNOVATIVE MANUFACTURING IN Food

Co-Authored: Natalie Chiu, Jade Phillips, Sarah MacMillan

1. Executive Summary

Summary:

In January 2009 the RSC/IChemE report Food: The Vital Ingredient was launched at Portcullis House and reported on the need for fundamental research within virtual centres of excellence, in order to keep the UK food manufacturing industry at the forefront of global food science and innovation. The importance of such is evidenced in the fact that the food and drink manufacturing industry is the biggest manufacturing sector in the UK – bigger than the automotive and aerospace industries combined. The food supply chain employs almost 4 million people and generates £112bn of value to the UK economy each year and contributes £28.8bn to the economy. Three centres were funded in 2013 ('**EPSRC Centre for Innovative Manufacturing in Food (CIM)**', the 'Centre for Sustainable Energy Use in Food Chains' and the 'National Centre of Excellence in Food Engineering'), which collectively have developed 80 researchers (future research leaders), enabled a national network of leading academics to be developed and which have acquired £17m in additional funding. The funding for these three centres finishes in 2019.

The EPSRC CIM in Food, has been led by the University of Nottingham's (UoN) Biomaterials group and also involves the Centre for Formulation Engineering at the University of Birmingham (UoB) and Loughborough University's (LU) Centre for Sustainable Manufacturing and Recycling Technologies (SMART). It was initially proposed to EPSRC by PepsiCo International in 2012, had an additional 13 letters of industrial support and received £5.6m from EPSRC and £1.1m of support from the participating universities.
Outputs from the Centre, including CIM conference presentations, publications and previous Annual Reports can be found at:
http://www.manufacturingfoodfutures.com/reports/reports.aspx .

Since its beginning at the end of 2013 it has interacted with over 120 companies, either attending annual research conferences (which have boasted esteemed international speakers), workshops probing new directions such as Additive Manufacturing (3D printing of food) and Food Waste Valorisation, or secondments of industry staff into the CIM or CIM researchers practicing knowledge exchange in their interactions with industry. It has been involved in the development of the KTN/FDF '**Pre-competitive vision for the UK's Food and Drink Industries'** (Dec 2013), and as a result of two CIM run workshops in co-creating funding opportunities of the future, to the IUK/KTN's '**Food Sector R&D Need & Alignment with the 2017 Government Industrial Strategy**' (Feb 2018). Indeed the outputs of the workshops were shared back in Portcullis House in December 2017 at the Parliamentary and Scientific Committee & All-Party Parliamentary Group for Food and Drink Manufacturing discussion meeting and published in **Science in Parliament** (Spring 2018), where a vision for unifying the three centres funded in 2013 was unveiled, ***to make the UK the most efficient converter of biomass to deliver safe food for a healthy nation with the lowest environmental impact***. The scientific barriers to be addressed are identified as: 1) to develop novel processing routes capable of valorising new sources of biomass (including waste re-use) and manufacturing healthy products tailored to the needs of consumers (e.g. customisation for nutritional requirements), and 2) to develop efficient systems that integrate supply chains with manufacturing requiring less resources (e.g. through use of smart monitoring), creating two new Grand Challenges: **Sustainable conversion of all biomass to safe and nutritious food for a healthy population**, and **Future-proofing today's supply chain to deal with tomorrow's finite resources**.

The CIM has delivered against its initial targets, which have been the forerunner to the desired pre-competitive areas and have published 140 peer reviewed publications and developed 10 patent cases

while developing researcher and academic careers, with 2 promotions to Professor, 3 researchers given permanent academic tenure, and post-doctoral and PhD researchers progressing into attractive industry roles. In total the CIM has developed the careers of over 60 researchers. In doing so it has been used as an umbrella to stimulate further work, leading to an additional £6.5m of research funding. Notable additional projects funded/delivered in the timeframe of the CIM are 'Transforming wet perishable food waste streams for high value human consumption' (TS/K003984/1), with Nottingham working with University of York (UoY) and 10 food companies valorising fibre from citrus waste, fine-milled pea vine, BSG aleurone protein and protein separation from out of specification potatoes; 'NewTrition: ReNEWable, sustainable nuTRITION' (2016-2019) funded by Newton-Bhabha (TP/P003826/1), seeing Nottingham working with PepsiCo, Siddarth Starch and the Indian Institute for Food Processing Technology on potato, vegetable, oat, grape, pomegranate and black gram waste; 'Whole systems understanding of unavoidable food supply chain wastes for re-nutrition' (2016-2018) funded by EPSRC (EP/P008771/1) with Loughborough, Nottingham and University of York (UoY) working on citrus and pea waste streams, developing waste flow modelling and environmental analysis through LCA to enable socio-techno-economic evaluation through cost-benefit analysis, risk analysis and systemic barriers exploring the gap between concept and final implementation; and 'Formulation for 3D printing: Creating a plug and play platform for a disruptive UK industry' (EP/N024818/1) linking Birmingham with the Institute of Advanced Manufacturing at Nottingham and spanning the food and pharmaceutical industries.

This increased activity in the area of food research has also prompted institutional investment at Nottingham (£20m) and Birmingham (£12m), with investments in Future Foods Beacon of Excellence, Food Process Engineering and Healthy Food Manufacturing.

The virtual centre of the future, serving a thriving research and innovation based community, both industrial and academic, is still needed to build on the foundation laid by the CIM to provide knowledge-based solutions relevant to all businesses in the sector from micro-SMEs to national and multinational providers.

Vision and organisation:

The EPSRC Centre set out to meet the challenges of global food security through developing world-leading technologies, tools and leaders, tailored to the specific needs of short shelf-life food products, focusing on two specific Grand Challenges: 1) Innovative materials, products and processes and 2) Sustainable food supply and manufacture; in six research themes: Upgrading of ingredients for improved resource utilisation, Food manufacturing for healthy diets and lifestyles, New processing technologies, New flexible manufacturing processes, Eco-Food manufacturing, and Sustainable Food Supply Chain.

What is interesting to note is that in February 2019 the International Union of Food Science and Technology (IUFoST) set out its **Global Challenges and the Critical Needs of Food Science and Technology**, identifying seven 'Missions'. In Table1 it is plain to see the alignment not only of the CIM's initial research areas (written in 2012), but also the Research programmes identified in the vision presented in 2017/18. Additionally, these would support and play into the 5 areas identified by the KTN's Food Sector Strategy group in its alignment with the 2017 Government Industrial Strategy (18 companies, 6 research organisations / institutions, 2 funding bodies and 10 universities) and are aligned to Global Challenges.

Table 1. Relevance of the CIM Research Themes and Future Vision.

EPSRC CIM in Food Research Themes (2012)	5 Food & Drink Sector R&D Needs: Alignment with Industrial Strategy (2018)	Global Challenges and the Critical Needs of Food Science and Technology (2019) 7 Missions	National Centre Research Vision (2018) Currently un-funded
Upgrading of ingredients for improved resource utilisation	2. Side-stream valorisation 3. Sustainable new food sources for nutritional foods	1. Introduce more diverse and sustainable primary production 3. Eliminate material waste in production, distribution and consumption	Production and characterisation of clean/green – minimally processed current and new ingredients from biomaterials
New processing technologies	5. Digital manufacturing	2. Develop new processes and systems, to ensure more sustainable manufacture	Microstructure engineering through equipment redesign
Food manufacturing for healthy diets	1. Reducing food energy density	5. Provide affordable and balanced nutrition to the Malnourished 6. Improve health through diet	Product macrostructure design for textural contrast and controlled processes of digestibility
New flexible manufacturing processes	4. Flexible and scalable manufacturing	7. Integrate Big Data, Information Technology and Artificial Intelligence throughout the Food Chain.	Low energy and water processing, including Process Intensification Process design for minimal or zero impact cleaning Sensing for self-monitoring adaptive processes, through digitally enabled processing for Mass Customisation and Flexible Manufacturing
Eco-Food manufacturing		2. Develop new processes and systems, to ensure more sustainable manufacture 3. Eliminate material waste in production, distribution and consumption	Low energy and water processing, including Process Intensification
Sustainable Food Supply Chain	3. Sustainable new food sources for nutritional foods	2. Develop new processes and systems, to ensure more sustainable manufacture	Low energy and water processing, including Process Intensification Predictive models for future supply chain design
		4. Establish complete product safety and traceability	Process design for minimal or zero impact cleaning

Research Scope and the Manufacturing Research Challenges

The focus of the Centre spanned the manufacturing paradigm from the technology / process level through to production and supply chain level, where such a connection provided researchers with a new way of thinking. This was facilitated by their attendance at conferences and workshops organised by the CIM, exposing the latest challenges from Industry (Mondelez, Jacobs Douwe Egberts, Siemens, Martec and Global 78), covering areas such as Industry 4.0, processing tonnes of material with exact functional requirements, engineering a global food system, self-optimising clean-in-place and sustainable supply chains; Charities / NGOs (WRAP, Forum for the Future and FoodWastenet) identifying challenges in valorising food waste and co-products, and manufacturing sustainable diets; National and International Academic perspectives on the developments in tacking foods' manufacturing challenges from Pontificia Universidad Católica de Chile, ETH Zurich, University College Cork, Wageningen UR, Nile University, the Universities of Edinburgh (UoE), Huddersfield, Leeds, Manchester (UoM), Oxford, York and Brunel University London (BUL) and Sheffield Hallam University (SHU); and parallel activities from other Centres, namely RCUK Centre for Sustainable Energy Use in Food Chains and National Centre of Excellence for Food Engineering. Two workshops on additive manufacturing (one delivered with KTN) and one on waste valorisation (co-hosted with 'Whole systems understanding of unavoidable food supply chain wastes for re-nutrition' (EP/P008771/1) attracted industry and academic participation, and the centre hosted the 2nd (Birmingham) and 3rd (Nottingham) UK Hydrocolloid Symposium.

The foci of the Research Themes were:

- New processing technologies: explore the use of novel processes, e.g. Microwave Vacuum Drying (MVD) for use in the commercial manufacturing of food structures.
- Upgrading of ingredients for improved resource utilisation: examine the recovery and valorisation of natural materials and the transformation of waste streams.
- Food manufacturing for healthy diets and lifestyles: investigate how to manufacture healthy, nutritionally balanced and wholesome foods.
- New flexible manufacturing processes: develop to address research and industry needs, e.g. distributed manufacturing
- Eco-food manufacturing: develop strategies, methodologies and tools for the food sector to measure and maximise its resource efficiency in production.
- Sustainable food supply chains: develop tools and strategies to produce the right amount of food, at the right time, in the right place using minimum resources.

In the course of developing the research arena and those researchers involved within it, in 2016 the CIM embarked on a future gazing exercise, which was then presented to the Advisory Board, and subsequently formed the basis for the two co-creation workshops with industry (March and October 2017), and then the outline for a Future Manufacturing Research Hub call (unsuccessful).

It was however in line with the National and International needs, where the Industrial Strategy white paper (2017) identified the need to strengthen partnerships with industry in the Food and Drink Sector, 'from farm to fork', and through the Courtauld Commitment to deliver a 20% per capita reduction in food waste by 2025. Additionally, moving towards a regenerative circular economy it identified a new Bioeconomy Strategy that will develop new low carbon bio-based products and processes, and the need for zero avoidable waste and a doubling of resource productivity by 2050. Also there is a requirement to transform food production, as the world will need 60% more food by 2050 to allow us to feed 9 billion people, requiring a significantly more efficient and sustainable system. In response the IUK/KTN Food Sector R&D Need & Alignment (2018) was published, founded on the CIM workshop outputs from October 2017. The 'Made Smarter Review 2017' identified a £55.8 billion opportunity for the Food and Drink sector over the next ten years through the adoption of currently known digital technologies. The High value manufacturing landscape 2016, interim report highlighted both 'Opportunity and Additionality' for a range of technologies covered within the evolving vision, e.g. Supply chain and business model innovation, Process engineering including: small-scale efficient manufacturing equipment and improved cleaning processes; Zero-waste manufacturing, Flexible and rapid manufacture including small-scale processing, late customisation and Intelligent automation. It also identifies sector-specific challenges, particularly as regards the bioeconomy, relating to new, sustainable food manufacturing processes, reducing energy and water usage mitigating increasingly volatile resources in the low carbon economy. In the Science and Innovation Audit (SIA) (2016) the Midlands Engine identified opportunities for major productivity growth in efficient food processing, zero-waste food chains, and food product innovation. This was mirrored by SIA (2017) where the Northern Powerhouse identified that the bioeconomy will have a major part to play in the transformation of global systems, the production of biomass and the conversion of renewable biological resources into value-added products, such as food. Additionally, the Foresight (2013) - The Future of Manufacturing stated that manufacturing local to consumers to deliver exceptional value is a trend already seen in the Food and Drink sector. In an international context the ETP Food for Life Strategic Research and Innovation Agenda (2016): 'Food for tomorrow's consumer' acknowledged an urgent need for increased private and public investments in research and innovation in order to secure Europe's role as a leading global provider for safe and healthy foods, and the trend towards a need for alternative food sources, and less refined, more natural food ingredients. In their call to action, EU through the Food EIT is investing in excess of £100m to develop new food production and delivery models to provide better access to food, through developing a more consumer centric flexible, dynamic and sustainable food system. Additionally, the UN Sustainable Development Goal 12.3 on Sustainable Consumption and Production: doing more and better with less, states the need for halving per capita global food waste, from the current 30% waste, and reduction of food losses along production and supply chains, including post-harvest losses by 2030. Wrap UK, aligned to the Courtauld Commitment 2025, indicate a need to find innovative ways to make best use of wastes and surpluses.

Therefore the new Research Challenges (Programmes) include:

RP1: Production and characterisation of clean/green – minimally processed current and new Ingredients from biomaterials: *To develop sustainable wet biomass processing, avoiding the need for energy intensive drying and allowing minimal refining to create new materials and the ability to use pre-processing to limit variation in ingredient / biomaterial properties. This will allow the development of innovative, eco-efficient and value-added ingredients for both food products and low substrate flexible paper packaging from renewable resources (starch & cellulose) to replace petroleum-based barrier films.*

RP2: Microstructure engineering through equipment redesign: *To design-in process flexibility using physical effects (e.g. efficient mixing, electrical fields) in processing to assemble primary ingredients into generic meso-units that will allow flexibility in the types of ingredients used. Molecular to micro-scale processing will be developed to engineer the functional performance outcome. Intelligent processing will be applied in the matching of machine-coating characteristics with materials / ingredients being processed.*

RP3: Product Macrostructure design for textural contrast and controlled processes of digestibility: *To design and develop novel processing routes that control the product structure during drying to allow* *for controlled rehydration kinetics during consumption, creating new textures. Engineering principles will be used to link product performance to key product characteristics and material properties required in oral and digestive processing. In-vitro and in-silico tools will be developed to predict physiological outcomes. Validation will be assured through the development of new sensor technology to optimise levels of nutrients in process, product and body i.e. providing optimised bioaccessibility.*

RP4: Low energy and water processing, including Process Intensification: *To investigate and develop innovative and flexible processes to significantly reduce energy and water demand and to deliver higher quality food products with increased throughputs and zero or minimal waste and environmental impact. New process design approaches will explore and exploit the full potential of novel innovations in low carbon heating technologies (e.g. microwaves, ultrasound and ohmic heating), low embedded carbon material as well as in-line non-invasive water flow monitoring and control systems.*

RP5: Process design for minimal or zero impact cleaning: *To design processes to eliminate cleaning through antimicrobial coatings and 'non-stick' low friction, hard, corrosion resistant surfaces that resist fouling as well as efficient detection of endpoint and control of cleaning to predict of the cleaning behaviour of equipment from knowledge of the geometry of the equipment and the product rheology. In addition, novel technologies such as Plasma to activate water and decontaminate process equipment will be investigated.*

RP6: Predictive models for future supply chain design (e.g. Decentralised and Distributed Manufacture & Distribution): *To define and develop predictive modelling processes and tools for the future digitally enabled food supply chains capable of supporting a resilient whole-system approach to a circular and efficient use of resources.*

RP7: Sensing for self-monitoring adaptive processes, through digitally enabled processing for Mass Customisation and Flexible Manufacturing: *To develop novel, modular, flexible, reconfigurable self-learning automated systems with IoT architectures which will enable efficient Just-in-Time procedures that will be fully responsive to a volatile e-commerce market. Existing and novel sensors to characterise structure will be incorporated into inter-operational communication and data architectures that will support connectivity across the complete supply chain, and ensure total product traceability and data security.*

The team assembled to overcome these barriers would build on the successful EPSRC Centre for Innovative Manufacturing in Food (2013-19: UoN, UoB and LU), the 'Centre for Sustainable Energy Use in Food Chains' (RCUK funded 2013-19: BUL, UoB and University of Manchester (UoM)) and the 'National Centre of Excellence in Food Engineering' (HEFCE funded 2013-19: SHU), which collectively have developed 80 researchers and acquired £17m in additional funding. Additional inclusion would come from the Soft Matter Physics capability at the University of Edinburgh (UoE), the Green Chemistry Centre of Excellence (UoY) and the Control Systems Centre (UoM). The interconnections between the research programmes can be seen in Figure 1.

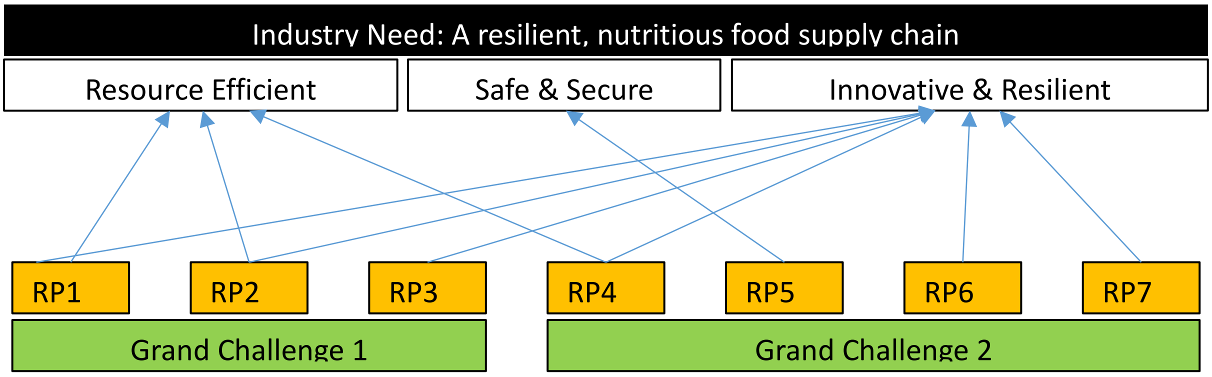

Figure 1. Multidisciplinary approach meeting the long term needs of the Food & Drink Industry.

Quality, timeliness and novelty of the work

In June 2016 the Centre underwent its Mid-term review, assessed by a multidisciplinary and International panel (Dr Nina Sweet OBE, WRAP UK; Dr Ad Juriaanse CEO NIZO, NL; Professor Allen Foegeding, William Neal Reynolds Distinguished Professor, Department of Food, Bioprocessing and Nutrition Sciences, North Carolina State University, USA; Professor Camille Michon, AgroParisTech, France; Dr Jacinta George, Head of Ingredient Functionality, Mondelez, UK; and Prof Duncan Hand, Heriot-Watt University - EPSRC Centre for Innovative Manufacturing in Laser-Based production Processes) chaired by Professor Ken Young (Technology Director of the MTC). The panel met with the Centre leadership team, but then separately with the researchers, associated academics and members of the Advisory Board. Their recommendations can be summarised as follows:

"The Food CIM fulfils a clear need to develop early stage research for the food manufacturing industry and also to deliver a stream of high calibre research capable scientists into the UK food industry. The CIM is running well and already delivering strong academic outputs. It is still very early to see industrial impact but there are patents that indicate that this will follow. The ***routes to impact*** need to be more clearly identified however. The food industry is a very diverse sector and it is recommended that more resource and effort is directed into ensuring that impact is maximised. The major challenge now for the leadership team is to ***create a strategy*** for the future to ensure continued funding. This is also an opportunity to increase the engagement of the junior academics in the future leadership of the centre".

They also noted that "the funding of the centre was creating a unique environment for food research", and "there was great consensus that Food CIM was strategically important and that it is essential that it should be sustained beyond the current funding". There was a "need to create and communicate a strategy for the future", and that "efforts are made to start to expand the network of the CIM and start to transition towards a hub model to prepare for future funding bids".

As outlined above, these recommendations were acted upon, involving the CIM community: researchers, academics, advisory board, external academics, and industry.

Future Outlook

The Future Research Manufacturing Hub bid was not successful, and therefore the team assembled to meet the needs at a National level has disbanded. There is still active engagement however with the Food Sector Council, through the FDF and DEFRA, and into the National Food Strategy, being developed currently, through discussions with LEPs regarding their local innovation strategies, and with the Midlands Engine. This work goes beyond EPSRC remit, and fits with an evolving UKRI, where physical, biological and social sciences are being combined to solve the big challenges of a resilient and nutritious food supply chain. However, the work outlined may be split up into bit sized chunks in the developing areas of interest, such as the Circular Economy, Digitisation of the Food Industry and Energy efficiencies.

The remainder of this report will focus on the outputs from the research carried out in the CIM (and associated projects).

2. National and International Significance

Since its inception in 2013, the CIM has established itself as a national resource supporting the UK food sector. Its academic partners have developed and delivered a plethora of outreach, engagement and impact activities. The CIM has connected with other research groups nationally and internationally, establishing an extensive network across the sector. Through our activities and engagement, we became a UK National Centre for the food sector.

Engaging the research community:

A highlight of each year since the CIM's foundation has been the **EPSRC CIM in Food Conference**. Each of these events brought together CIM members from industry and academia as well as other stakeholders across the sector. The four conferences showcased our activities and research in food futures, including food materials and structure, minimising waste and valorisation, and sustainable food production. We have hosted world-leading experts and attracted national and international delegates. Attendance at the conferences grew year on year and they formed the basis of several research partnerships and the creation of the new vision for food research outlined earlier in this report.

In addition, CIM partners have delivered, attended and supported a wide range of events and activities to ensure that our work creates real impact across the sector. In particular, we have showcased our research at numerous international conferences. For instance, Ernesto Tripodi and Panagiotis Arkoumanis presented their work on emulsions produced via Confined Impinging Jet Reactors and Rotating Membrane emulsification at the **11th European Workshop on Food Engineering and Technology** in Germany (April 2017). Ernesto also gave an oral presentation on Turbulent mixing in Confined Impinging Jet Reactors for the production of emulsions at the **16th European Conference on Mixing**, Toulouse, France (September 2018) which attracted participants from over 30 countries.

We also presented our research on food design at **The Barriers and Challenges of 3D Printing in Innovative Food Manufacturing** (November 2015), the **Institute of Physics: Physics in Food Manufacturing Summit** (April 2016), the **IUFoST 18th World Congress of Food and Science and Technology** (July 2016) and the **Topical Research Meeting on Physics in Food Manufacturing** (January 2017). We presented work on particle stabilised emulsions and foams at the **RSC/SCI Colloids Group Meeting: Particles at Interfaces** (September 2016) and were invited to present on food structures at the first **IFSTAL Symposium: Technology – a sliver bullet for the food system** (January 2017).

Many of these conferences formed the basis for future collaborations, and others allowed us to specifically showcase the interdisciplinary strength of groups and individuals within CIM to identify and promote research partnerships, e.g. the **Engineering and Physical Sciences Research Conference** (October 2016). The **Systems Change Thinking - Creating Value from Unavoidable Food Supply Chain Wastes** (January 2018) also provided an opportunity to explore collaboration and potential commercial applications in the area of unavoidable food supply chain wastes as unique bioresources.

As well as attending major conferences, we also hosted the **2nd and 3rd UK Hydrocolloids Symposium** (September 2015 and 2017) on the themes of 'Hydrocolloids in Formulation Engineering' and 'Hydrocolloid Structures Determining Functionality'. These were one day events attended by over 100 delegates each from the UK, Spain, Thailand, China, Malaysia, Sweden and Iran. The events were designed to provide early career researchers the opportunity to highlight and share their research (34 speakers), while keynote talks from Dr Bill Frith (Unilever), Dr. Niklas Lorén (Chalmers University of Technology, Sweden), Dr. Carmen Boeriu (Wageningen UR Food & Biobased Research, The Netherlands), Professor Alan Mackie (University of Leeds), Dr Alan Smith (University of Huddersfield) and Professor Henk Schols (Wageningen UR, the Netherlands) outlined the directional aspects in the field. Posters also highlighted the diversity of hydrocolloid research and promoted the exchange of ideas between disciplines for hydrocolloid application.

These outreach activities have been successful in creating new research projects through academic partnerships, and new industry funding totalling a further income to the CIM of **£6.5m**, with funding from EPSRC (Future Formulation, Studentships, Circular Economy, CDTs), Innovate UK (Technology Inspired Innovation, Improving Supply Chain Efficiency, Small Grants, Health and Life Sciences 2), European Commission (Fellowship), BBSRC (DRINC, NIBB, IBB, DTP), Newton-Bhabha and GCRF, leveraging funding to Industry and direct support from Industry (PepsiCo, Unilever, Nestle, Mondelez, DEVRO, Martec, Bakkavor, Marks & Spencer, Science in Sport, Diageo, Pladis and Campden BRI). Ambitious bids have also failed **(£30.2m** to EPSRC (Food Supply Chains, Future Manufacturing Research Hub, Prosperity Partnerships, Global Development Challenge), Wellcome Trust and Innovate UK) showing a drive for pushing the boundaries further and fulfilling the requirements of 'acting as a **National Centre**' (Acting for the national good, Building community, maintaining visibility and reputation, Initiating research translation and wider engagement, Developing strategy, Influencing policy, coordinating equipment resource, and Providing information).

Beyond the research agenda the interactions with research partners also provided **ECR secondment opportunities** to RISE - Research Institutes of Sweden, Unilever (UK and the Netherlands), Wageningen UR, DEVRO, Samworth Brothers, Greencore, Rich Products Corporation (USA) and PepsiCo.

We have also hosted the **Oracle** and **EHEDG** annual conferences.

Education:

As well as our research and academic engagement, the CIM worked extensively to engage students at both school and university levels through the real-world significance of food sciences. At the **Year 11 Pathways to STEM** event (September 2016) and the **Food Science Summer School** (July 2017), both at Nottingham, teams of research students and staff from the Centre held interactive demonstrations and discussions to inspire and encourage students to consider studying STEM subjects generally and food science in particular. Nottingham also hosted the three-day **Sutton Trust Summer School** (July 2017) at which students learned about food microstructures by taking part in interactive workshops to create structures regularly found in food products.

One of our CIM researchers, Mattia Cassanelli, also delivered an exciting three-day training course on **Teaching Food Science and Engineering** in the **Cooking Master School** at E.N.A.I.P. Tione di Trento (December 2017). The course was both theoretical and practical and introduced students to techniques such as spherification, drying and caffeine extraction, as well as the influence of water on chocolate, blooming, 3D food printing, emulsion stabilisation, quiescent, fluid gels, and the role of different ingredients in ice cream. At the end of the course students created their own desserts which were judged on creativity, oral presentation, the embedding of scientific terminology and organoleptic properties. The highest ranked sweet was a revised version of Sicilian Cannoli created using liquid nitrogen ice cream, cocoa gellan gum sheets and strawberry juice bites!

Knowledge transfer and engagement with industry:

A major prerogative of the CIM was to engage in collaboration with industry through research partnerships and knowledge transfer activities. In particular, we sought to help industry tackle current and future challenges in food production, sustainability and health, both in the UK and internationally. Along with the Knowledge Transfer Network, the Centre organised and delivered **Agri-food Opportunities in Additive Manufacturing** (April 2016), a pre-competitive workshop for the food industry which developed planning schemes (road maps) based on current issues and future needs. It also identified intellectual, technological, social and funding gaps in additive manufacturing for the agri-food sector. The EPSRC CIM in Additive Manufacturing were also involved in delivering this workshop, which in part led to the Centre's involvement with them in the Future Formulation 'Formulation for 3D printing: Creating a plug and play platform for a disruptive UK Industry' project.

The Centre presented at the **IFST Golden Jubilee Conference** 'The Fantastic Future of Food: Celebrating the past, looking to the future' (2014) with a talk entitled 'The Future of Food Engineering' and exhibited at the EPSRC **Manufacturing the Future Conference** (September 2015) along with Unilever and PepsiCo, presented its research on new food technologies at the **Marks and Spencer Innovation Day** (July 2016), and raised awareness of the sustainability challenges faced by the general public and industry due to overconsumption at the **IFST Spring Conference 'Food Sustainability: Waste not, want not'** (April 2016). We took part in the **Interface and Food and Drink Federation Scotland - Food & Drink Reformulation for Health** (February 2017), the **Roadmap for Food Futures Research Workshop** (March 2017) and the **BNF 50th Anniversary conference: Who is shaping the food choices of the future?** (October 2017), which brought together industry, government and academic specialists to consider how technology is addressing problems of food security, nutrition and climate change. Joanne Gould also presented her research on natural and sustainable food additives at the **Workshop on Innovations in Aerated Food Processing for Sustainability, Health and Life** (January 2017). This work replaces commonly used artificial stabilisers and emulsifiers, and as a result of her expertise Joanne was invited to speak at the **Campden BRI Bakery Technology Conference** (May 2018).

Internationally, Centre Director Tim Foster built relations between Indian research groups in two British High Commission delegations in 2013 and 2014, presenting at 'Foodpro', Confederation of Indian Industry (CII), and meeting the Indian Council of Agricultural Research, Department of Biotechnology, Council of Scientific and Industrial Research, chairing three CII roundtable discussions in Delhi, Chandigargh and Coimbatore, and visiting research institutes NABI, CIAB, IHBT, Panjab University, Mysore University, Central Food Technological Research Institute, Tamil Nadu Agricultural University, Indian Institute of Food Processing Technology. This provided a deep insight into promising Indian government directives and facilitated research collaborations between India and the UK. The Newton-Bhabha project between UoN, Pepsico, IIFPT and Siddarth Starch is an outcome of such visits. The project is delivering nutritious and affordable snacks to the rural and urban poor in India. Tim Foster was also involved in a FRIENZ (Facilitating research and innovation cooperation between Europe and New Zealand (BioEconomy Tour) discussing opportunities with University of Auckland, Massey University (the Riddet Institute), Plant&Food Research, Cawthron Institute, AgResearch and Fonterra R&D.

Public engagement, outreach and visibility:

Raising public awareness of our work, especially in the fields of improved nutrition and sustainability was vitally important. At the **Local Nexus Network for Redistributed Manufacturing Workshop** (December 2016), which was attended by the general public, politicians and researchers, we showcased the future of manufacturing and identified potential needs for research. A significant outcome of this event was a report which was made open to the general public and which is expected to be used by the UK Research Councils to influence future research needs.

https://www.centreforsmart.co.uk/publications/innovative-manufacturing-technologies-for-redistributed-manufacturing

Moreover, contacts were established which could support future projects and collaborations. Good links have been built with the Environmental Change Institute at Oxford, leading to a (failed) bid 'Food system extreme Event and Impact model for Stress Testing the UK and global food systems (FEIST)'.

In addition, a team of Centre staff participated in the **National Science and Engineering Week: Science in the Park** (March 2015) which was attended by more than 5,000 people. Through an interactive microstructure game we demonstrated how family-favourite foods are engineered. We ran interactive activities for families to explore how food manufacturers use ingredients to produce structure, texture and other sensorial properties in jelly sweets and aerated chocolate at the **British Science Festival** fringe (September 2015), and at **Discovery Communities Live** (2016), our team attended the **'Waste Less Save More'** workshop to connect companies and consumer groups tackling food waste and identifying how food waste can be reduced.

A major outreach activity was the CIM participating in the **Food Matters Live** exhibition for three consecutive years (2015-2017). Food Matters Live brings together members of the food and drink industry to enable collaboration and innovation and is attended by over 10,000 visitors each year. The topics covered ranged from food policy and regulation to sustainable food and drink manufacturing and population health and wellbeing. CIM partners were invited to discuss their research, present at seminars and debate policy with representatives from industry, academia and the government.

All three PIs have been on the KTN Food Sector Strategy Group for the past five years and have helped shape the KTN/FDF '**Pre-competitive vision for the UK's Food and Drink Industries'** (Dec 2013), and the IUK/KTN's '**Food Sector R&D Need & Alignment with the 2017 Government Industrial Strategy**' (Feb 2018). The future vision for food manufacturing research was shared in Portcullis House in December 2017 at the Parliamentary and Scientific Committee & All-Party Parliamentary Group for Food and Drink Manufacturing discussion meeting and published in **Science in Parliament** (Spring 2018). The CIM has also published its work and vision in **Impact** (Foster, Norton and Rahimifard, 2018, 6, 6-8), **Open Access Government** (January 2019), **The Journal of the Institute of Food Science and Technology** (2017, 31(1), 21-23)) and **the UK Manufacturing Review 2015-2016**.

Doctoral training and skills development:

A major aspect of the Centre's success is the training and development opportunities it facilitated for early career researchers. Each partner University committed to funding PhD studentships which aligned to the grand challenges of the Centre in 'Innovative materials, products and processes' and 'Sustainable food supply chains'. In addition, the directly funded studentships from Industry increased this number to a cohort of 34 researchers (30 PhD and 4 MRes) who have been trained and our graduates have gone on to challenging roles in academia and industry.

From the following quotes the benefit of the CIM to the researchers is seen at a skills development, community and personal level:

- "I've learned from academics and professionals who are top in their fields" and the CIM has "formed an important platform in unifying researchers from a range of backgrounds to apply and share their knowledge". The researchers "have been lucky enough to have access to an extremely broad variety of techniques", and "received training for different types of equipment, both by colleagues and attending courses given by the company of the equipment". They "truly believe that I would not have received such a wealth of training anywhere else".
- They have "felt part of a research community, in particular through participating in international and national conferences and events", attaining "an understanding of the challenges faced by the food industry", and able "to collaborate with a large number of researchers within the CIM group".
- Personal growth is acknowledged through having the "opportunity to publish papers in peer reviewed journals", and having "vastly improved many research skills, in particular, report and thesis writing". Attending "the CIM conferences as well as the Food Matters Live as an exhibitor" provided "valuable feedback" and "opportunities to work with several industrial partners, which will benefit future job prospects". Additional benefits are seen in "improving networking skills" and "several workshops and meetings were organised and allowed us to improve soft skills such as teamwork, decision-making, communication and problem-solving". Researchers have also become members of the "committee IChemE Food & Drink Special Interest Group" and have chaired the IFST Student Group.

Below, some of our students describe their experiences in the Grand Challenges in which they worked.

Innovative materials, products and processes

Duo Duo Wang - Characterisation of CRISPR mutants targeting genes modulating pectin degradation in ripening tomato - Cell wall structural remodelling including solubilisation and depolymerisation of pectin polysaccharides, and depolymerisation of hemicelluloses normally occurs during the process of tomato fruit softening, which is a consequence of the combined action of multiple gene products involved in modulation of cell wall structure. The tomato genome sequence contains more than 700 gene models annotated as having cell wall-related functions; Of these around 50 are expressed during fruit development and ripening (Tomato Genome Consortium, 2012). However, only a small proportion of these genes are highly up-regulated during the ripening process. In this project we are focusing on the six most highly ripening-related cell wall genes to test if knocking them out by DNA editing can influence the progress of tomato fruit softening and extend shelf life. Results indicated that the CRISPR/Cas9 system was efficient in tomato for generating Double Strand Break-induced target gene editing. Germ line transmission and heritability analysis of CRISPR/Cas9-generated mutations indicated that gene mutations could be passed to the next generation. Enzyme activity was significantly reduced in CRISPR transgenic lines compared with the control azygous wild-type line. One of these genes was found to be responsible for a substantial portion of tomato fruit softening. Immunocytochemistry is underway on a range of transgenic plants with altered cell wall enzyme levels. **Duo Duo took up a postdoc role at the University of Florida upon completion of her PhD**.

Mattia Cassanelli - Influence of gel microstructure on drying and rehydration processes for food industry applications - I started my PhD project on drying technologies in the food industry in March 2015 after graduating in Materials Engineering at the University of Trento, Italy. My research investigated drying techniques, such as supercritical fluid drying and freeze drying, used in the food industry. Particular attention was paid to hydrocolloids and to the effect of their structure on drying/rehydration processes. This work provided an understanding of how the drying technique can modulate the bulk porosity of gels and how the rehydration rate is consequently affected. Its novelty lies in the comparison of drying techniques in terms of generated porosity, without changing the system formulation. Mattia has completed his PhD and is now **International Technical Sales Executive at Biopharma Group**.

Simone De Chirico - Oil bodies as a source of naturally pre-emulsified oil - The process of oil extraction and purification form oleaginous seeds using organic solvents, has a high environmental impact, and is hazardous due to flammability and risk of explosion. During this process the oil is released from natural spherical organelles named 'oleosomes'; once the oil has been refined, it is re-encapsulated in the form of emulsion droplets using surfactants and antioxidants for incorporation into a range of foods. Oleosomes are generally between 0.2 and 2.5 µm in diameter. They are made of a core of triacylglycerol surrounded by a layer of phospholipids with embedded surface active proteins (e.g. oleosins). This project focuses on the extraction and characterization of intact and pure oleosomes as a natural source of pre-emulsified oil to be used in a range of food applications. The extraction method used for the recovery of oleosomes affects their physiochemical characteristics, such as particle size, purity (extraneous proteins and polysaccharides can be carried over from the seed matrix), and zeta potential. The extraction of these natural oil droplets using an aqueous process is more environmentally friendly, reduces the hazard and, based on preliminary estimates on small scale production, uses one-fifth of the energy consumed. Moreover, the co-extracted proteins can be then exploited in the preparation of protein isolates. The project has demonstrated a beneficial effect of the use of buffer systems instead of simple distilled water as an extraction media and have created emulsions of intact oleosome with similar physiochemical characteristics to the traditional preparation methods. A journal paper has now been published in Food Chemistry, entitled 'Enhancing the recovery of oilseed rape seed oil bodies (oleosomes) using bicarbonate-based soaking and grinding media'. Investigators are now optimising the combination of time-temperature parameters to extend the stability of oleosome emulsions. Since completing his PhD he has become a **Medical Information Specialist in ProPharma Group**, a medical Information company.

James Huscroft - Investigate process-based modification of lignin-rich feed material into functional food particles - The aim of this project is to explore process manufacturing routes to impart emulsifying ability to a range of lignin-based feedstocks and to assess their commercial viability as a future functional food ingredient. Relocation of lignin from the plant cell walls onto the particle surface using a hydrothermal treatments may alter the hydrophobicity of the particle. Brewers' Spent Grain (BSG), a widely available and lignin-rich by-product, has been selected as the initial feedstock a being. The project is investigating established thermal process technologies and is also comparing microwave technology to functionalise the feedstock imparts superior functionality.

Holly Cuthill - Lignin-based ingredients for healthy snack foods - The hydrophobic character of lignin renders lignin-rich feedstocks from food waste interesting for the generation of emulsifiers and foam stabilisers through extraction and precipitation into micro-particles. The aim of this project is to design a lignin-based particulate food ingredient with controlled surface hydrophobicity. Extraction and precipitation approaches discussed in literature predominately involve solvents or processing aids which would preclude application of the particles in food systems. A method has been developed to relocate and extract lignin which may be suitable for food application. The current work focuses on functionalising this extract by manufacturing and characterising the lignin-based microparticles.

Sonia Holland - 3D Printing using edible biopolymers - This project investigates the use of edible materials in established Additive Manufacturing (3D printing) processes to enable incorporation of 3D printing to food manufacturing. Thus far application has been extrusion (via 'fused deposition modelling' approach) of paste-like or meltable materials e.g. chocolate, pasta dough, mashed potato etc to create interesting geometries, therefore mostly for aesthetic appeal rather than specific functionality and at a resolution no less than 0.5 - 1mm feature size due to the limitations of FDM. Binder jetting involves using an ink jet printer head to deposit a binding material in an exact pattern onto a powdered material bed sequentially, typically usually 100μm thick layers of powder alternating with a layer of the binder, to result in a 3D object. With this technique dietary fibre is utilised to create structures relevant to the food industry. High viscosity jetting has also been employed with fluid gel feedstocks to produce 3D printed gels. Three journal manuscripts are now published in the Journal of Food Engineering, Carbohydrate Polymers and Food Biophysics, along with a book chapter 'Creation of Food Structures Through Binder Jetting', *In:* Godoi FC, Bhandari BR and Prakash S, eds., Fundamentals of 3D Food Printing and Applications, Elsevier Academic Press. Upon completion of her PhD Sonia joined the **DIAGEO Global R&D Centre.**

Eleanor Warner - Edible filaments for fused deposition modelling - There has been a great deal of interest in the possibility of creating personalised food through the use of additive manufacturing. However, there is still much to understand in regards to the formulation and printability of ingredients if this technique is to become a viable production route. My project involved designing and developing a new print head for an extrusion based additive manufacturing process in order to print edible materials which undergo a phase transition. Initially plastic materials (PLA and ABS) which are already involved with an extrusion based additive manufacturing process were investigated. The properties of mixed hydrocolloid systems (gelatin with various secondary biopolymers) were then investigated and their rheological properties were manipulated in order to tailor them for the extrusion process. After printing these edible materials, a set of design rules were determined in order to be used as a guideline of printability for numerous materials, which undergo a similar transition.

Panos Arkoumanis - Particle stabilised emulsions through membrane emulsification - My work investigates the potential to produce particle-stabilised emulsion microstructures through a rotating membrane device. The advantage of RME (and in general membrane emulsification) against conventional techniques is the low shear and low energy used and the controllability of the emulsion microstructure. Droplets are generated one at a time by adjusting the oil flux (trans-membrane pressure) shear at the membrane surface (rotational velocity) and the membrane characteristics (pore size, material, porosity). This results in a very homogeneous product (uniform drop size). However, particles do not possess the same level of interfacial affinity as surface active species, nor the necessary energy to adsorb to the oil-water interface, due to the poor hydrodynamic conditions close to the membrane surface. Our work shows that this could be improved by utilising a co-stabilisation strategy (particles plus small amount of emulsifier) or altering the hydrodynamic regime with mechanical means (stationary plates in the emulsion production vessel).

Chris Clarke - Food Foams: Drainage at the Microscale - Foams in the food industry cover a broad variety of products, forming both essential structural properties as well as a degree of luxury. Due to their unstable nature, however, foam longevity is often an issue. The 'drainage' of liquid between bubbles is a primary mechanism for foam collapse, and represents a complex multi-scale process uniting molecular level interactions with bulk foam characteristics. My research project is comprised of a custom experimental setup and measurement technique that allows the controlled exploration of microscale liquid flows through the channels between bubbles.

To date, the setup has proven capable of measuring the surface shear viscosity, a key drainage parameter, to an unparalleled degree of accuracy for soluble surfactants. These values have been shown to surpass the measurement sensitivity of the most sophisticated techniques currently available, making this a potentially important step forward in understanding the dynamics of these interfaces. Furthermore, the nature of the technique provides the first direct link between idealised theory and experimental observation, something which has so far been sorely lacking in literature. As a consequence, it has been possible to *visually* confirm key microscale predictions of the standard drainage theory, therefore adding much needed experimental evidence to the limited supply currently available.

Gladness-Marry Manecka - Re-dispersible dry emulsions - My project studied the effects of different drying processes on the drying and rehydration of oil-in-water emulsions. The focus was not only on the direct effects of drying but also on how tailoring the formulation of the emulsions based on the particular drying process could affect the outcomes. The aim was to produce oil-filled powders from oil-in-water emulsions that would be reconstituted after the addition of water. To be considered reconstituted the droplet diameter, the viscosity and the mouthfeel of the emulsions had to be similar before and after drying and rehydration. To measure the extent of the effects of drying on the emulsions the dry powders were analysed in terms of particle size, shape and powder wettability, a factor determining the rehydration of the dry emulsions. For this study the emulsifier chosen was a protein-polysaccharide conjugate best known as “Maillard conjugate” or “glycoconjugate”. This emulsifier has shown not only increased stability to temperature changes, but also enhanced stability due to the thicker interfacial membrane it forms at the oil-water interface of emulsions. For specific applications, it also displayed a better ability to resist environmental changes such as change of pH or ionic strength, and an increased stability at pH close to the isoelectric point of the proteins it is made of. The results of this study showed that Maillard conjugates were eligible candidates for the production of dry emulsions through both freeze-drying and spray-drying. Out of all results I gathered I made two majors findings: the stability of the emulsions to pH close to the isoelectric point of the proteins has been widely reported in literature. However my study showed that when using a pH sensitive polysaccharide, the emulsions were not stable at pH around the pKa of the polysaccharide. The second major finding is that using a protein-lactose conjugate when spray-drying emulsions increased the stability of the emulsions in comparison with lactose being introduced as a wall material. The amount of lactose could this way be considerably decreased.

John Noon - Microwave processing of native bioactive compounds - During my time with the CIM I have been involved in two major research projects. The first explores ‘**The use of a novel microwave antisolvent-precipitation technique for the synthesis of bioactive nanoparticles’**. This research focused on a novel Microwave Antisolvent-Precipitation (MAP) technique for the production of bioactive nanoparticles. This technique uses dielectric heating for the rapid removal of solvent from solvent-antisolvent mixtures (in which a solute is dissolved in the solvent) to facilitate the formation of aqueous nanosuspensions. Two model bioactive compounds, curcumin and silymarin, were used for this study. Our key findings included the fact that in the cases of Curcumin and silymarin, the rate of solvent removal was found to have no impact on the size or polydispersity of synthesised nanoparticles. Using MAP, unprocessed crystalline curcumin particles were size reduced from ~20µm diameter into highly monodispersed (PDI <0.1) amorphous nanoparticles of ~150nm diameter. This is known to enhance dissolution velocity and potentially, bioavailability. In addition, Curcumin nanosuspensions formed using the MAP technique were found to have significantly improved stability over synthesised nanosuspensions in which there had been no solvent removal through microwave heating due to the rapid removal of ‘diffusible solute’ in the nanosuspension mixture.

The second project, ‘**The use of Antioxidant Rutin Hydrate Pickering Particles to combat Lipid Oxidation in O/W Emulsions’** assessed the use of the natural antioxidant Rutin Hydrate Pickering particles for emulsion formulation. Experiments were conducted to assess the dual-purpose ability of RH to both provide emulsions with physical stability through acting as a conventional Pickering particle, as well as oxidative stability through antioxidant effects which would combat Lipid Oxidation

(LO). We found that RH produces emulsions which are capable of being physically stable for at least 14 days, and that it significantly retards LO. Moreover, emulsion droplet size was found to have a significant impact on the oxidative stability of emulsions.

Fabio Smaniotto - Understanding fluid gels to modify food texture - The production of fluid gels has been studied in recent years as an industrially scalable process using different types of hydrocolloids and production procedures. Fluid gels are concentrated suspensions of gelled microparticles that can be used as thickeners, gelling agents and replacements for fat content in foods. However, little research has been conducted on using these materials in the field of encapsulation, protection and controlled release of active compounds, despite the fact that hydrocolloids are largely used for these scopes both in the food and pharmaceutical industries. The scope of the project is to study the process of encapsulation of active ingredients inside fluid gels and to clarify how this affects the final properties of the materials. The encapsulation behaviours of vanillin, tryptophan, nicotinamide and ascorbic acid into alginate fluid gels have been investigated so far. Additionally, the freeze drying of these materials has been studied as a means to prolong their shelf-life and prevent the formation of bacteria and moulds.

Ernesto Tripodi - Development of Confined Impinging Jets: a low-energy perspective over the turbulent emulsification processing - In the food industry, an exciting research area focuses on the development of processing techniques that attempt to overcome the current limitations of both their bench scale (e.g. low throughputs) and industrial (e.g. large energy consumption) counterparts. This project aims to expand the processing functionalities that can be imparted onto simple as well as complex emulsions via Confined Impinging Jets (CIJs), which offer the possibility to create emulsion based microstructures by coupling low energy inputs to the potential of delivering high throughputs.

To extend the current understanding of CIJs, emulsification was carried out for a wide range of oil mass fractions stabilised by both surfactants and particles. CIJs overall performance was also evaluated against their equivalents as delivered through conventional emulsification routes. Finally, it was showed as CIJs processing permitted for the production of complex emulsions, thus opening an entirely new research pathway for the successful application of CIJs in the food sector.

Sustainable food supply chains:

Jamie Stone - Development of a framework for enhancing resilience in the UK food and drink manufacturing sector - Investigations of resilience in supply chains can be adapted to suit UK Food and drink manufacturers. This is particularly timely given the array of pressures facing food chains, from climate change, to population growth and increasing resource constraints, which manifest as volatility. Food and drink manufacturers are particularly exposed to such volatility given the highly complex and global nature of their supply chains and their typical reliance on a relatively small number of capital intensive manufacturing sites. Food is also different to generic resources due to factors such as shelf life and natural variability in terms of quality and quantities of food as a raw resource. In response, this research presents a conceptual framework which details how food and drink manufacturers can accurately identify their unique vulnerabilities. Then mitigate these in a way that is complimentary to the wider sustainability of the organisation. This conceptual framework is developed into a set of tools, presented in the form of a workbook, which enable a food and drink manufacturer to practically enhance their own resilience. This toolkit has been validated through two in depth industry case studies. Upon completion of his PhD Jamie worked briefly on the **Systems Change Thinking - Creating Value from Unavoidable Food Supply Chain Wastes** and is now a **Programme manager in the BBSRC Global Food Security** team.

Pedro Gimenez-Escalante - A multi - criteria decision support method for distributed and localised food manufacturing - The need for a shift towards smaller-scale local manufacturing has been highlighted by a range of factors such as changes in transport and labour costs, availability and access to materials, energy and water; and the need for long-term resilience to market changes. The unique attributes of food products make them particularly suitable for localised, distributed manufacturing as they require considerations for fresh perishable ingredients, stringent storage and health risks associated. This research aims to specify and develop four innovative 'Distributed and Localised Manufacturing' (DLM) models of food production. To achieve this, fifteen food product, process and system related assessment criteria are defined and used within a structured multicriteria decision support tool. This can assist in the identification of those food applications in which distributed localised manufacturing is economically feasible, environmentally beneficial and presents potential to support local economies. In addition, this enables the calculation of specific DLM suitability scores to guide strategic decision making towards the implementation of the most suitable DLM alternatives. The implementation of such DLM models will aid with the creation of more agile and shorter supply chains, the provision of customised/personalised food products in support of dietary requirements, lastly minimising the environmental impact and costs associated with food transportation. Upon completion of his PhD Pedro returned to Spain and is **setting up a family Brewing business**.

Guillermo Garcia Garcia - Waste flow modelling and life – cycle assessment in support of food waste valorisation - Food manufacturing is a complex process in which vast amounts of wastes are generated. Current strategies for dealing with these materials are rudimentary and of low value, including animal feeding and bedding, anaerobic digestion, composting, incineration, land spreading and landfilling. However, food wastes are valuable bio-resources. They contain a number of bio-based materials and chemicals with a range of potential commercial applications. This project aims to develop evidence-based, whole-system change, to recover unavoidable food wastes and use them to produce new food products.

With this aim, current practices for waste disposal are being studied to propose key indicators and novel solutions to characterise unavoidable food wastes. After analysing the reasons for waste generation, initial proactive whole-system solutions to eliminate waste are being proposed and examined, before developing reactive solutions for upgrading the remaining unavoidable waste. The main research focus is on developing technologies and processes to extract useful ingredients from unavoidable wastes and use them to create new food products. Finally, when alternative processes are identified, their associated ecological ramifications will be assessed to ensure the overall environmental impact is reduced. The proposed solutions will allow food manufacturers to improve their environmental and economic performance associated with food waste management. Guillermo worked on the **Systems Change Thinking - Creating Value from Unavoidable Food Supply Chain Wastes** and is currently working as a **PDRA at Loughborough University, funded by Enterprise Funding**.

Sandeep Jagtap - Utilisation of Big data analytics for improving the efficiency of food supply chains - In recent years, research interest in Big Data (BD) and the Internet of Things (IoT) concept deployment has increased significantly among researchers and practitioners within various manufacturing sectors. Application of such concepts within food supply chains (FSC) presents significant challenges in analysing the enormous amount of data, which often reveals many optimisation opportunities. This research focuses on the benefits of adopting BD and IoT concepts and technologies. Thereby, improving the resource efficiency of FSCs, with specific objectives of reducing food waste, minimising energy and water consumption. This is to be achieved through real-time monitoring and automatic data collection, which is related to resources (food waste, energy and water). Therefore providing opportunities for implementation of a continuous improvement approach for resource efficiency. Upon finishing his research in the CIM Sandeep took up a **Lectureship at the University of Lincoln**.

Farah Bader - Industrial Robots for flexible food manufacturing - Continuously changing consumer demands and an ever-growing range and number of regulations. Furthered by, increasing concerns over cost and availability of labour have put the UK food industry under significant pressure. Food Small and Medium Business Enterprises (SMEs) are set to be most affected. The systems for foodstuff handling and processing employed over the years are very inflexible and rigid. This has resulted in the need for product and process innovation in the industry, with flexible automation leading as the main growth opportunity. This flexible automation is often available in the form of industrial robots. However, their uptake for food handling and processing has been slow due to limited knowledge, resources and skills, especially within SMEs. Furthermore, existing methods for the planning, selection and installation of robots have been found to be either too difficult to navigate or not applicable to foodstuffs. This project aims to assist food manufacturers, particularly SMEs, in the planning and selection of industrial robotics for food applications. This is to be facilitated through the review and identification of existing industrial robotics applications. A decision support tool will present the user with recommendations based on their specific foodstuff and processing requirements on a single platform. The user will also be able to assess the recommendations economically and environmentally, ensuring holistic and informed decision making. This will then improve production flexibility, response to market and overall productivity of this manufacturing sector in the UK.

3. Our research and its impact

In the following sections an overview is provided of the work undertaken within each of the Research Themes, outlining the areas of innovation and development, and where the work has been introduced to and taken up by Industry partners. At the end of each section the future plans for the work are highlighted.

New processing technologies

Work has progressed on a number of fronts, identifying the underpinning material science to create new food microstructures, to minimise water and energy usage in manufacturing processes, to increase the efficacy of bioactive ingredients and to provide new materials for inclusion of air into food products. The work has been at a fundamental level, but industry interest has grown, with pick up of technologies by Science in Sport, Diageo and PepsiCo.

Themes:

- High quality dried products
- Use of mixed solvents for improved processability
- Low energy emulsification
- Design of functional particles
- Using air as an ingredient

Creating rehydratable microstructures

Work on drying and rehydration has been directed on two fronts, both evaluating potential technological advances in drying and developing formulations to provide enhanced future functionality. Dried products are ubiquitous in the marketplace and have been used extensively for preservation purposes and reducing transportation costs. Traditionally however, products destined for rehydration (i.e. ones not consumed in dried form) often have quality issues and therefore generally have a negative reputation among consumers. The main reason for this is that these products are often designed first and then undergo a drying and rehydration process which damages the often-delicate structures of things such as emulsions or gel networks and are often dried to extremely low moisture contents. Work within the CIM specifically focussed on recommending a microstructure approach which specifically designs structures with the drying process in mind thus creating higher quality final products. Technologically the projects explored utilising traditional air and spray drying along with more advanced freeze drying and experimental vacuum microwave drying, and supercritical Carbon Dioxide drying which offers significant energy efficiency/speed/quality.

From a formulation perspective two main structures were explored. Firstly liquid emulsion systems stabilised by conjugates allowed for creation of oil in water sub-micron emulsions with low moisture content and unchanged droplet distribution through freeze drying and rehydration. By utilising Maillard chemistry of common food materials a thick interfacial layer was created stabilising the emulsion droplets through the drying process, maintaining structure. These systems would have use in products such as salad dressings and soups, wherever an emulsion system is used. For gel networks, these materials often form the basis of many formulated foods (e.g. yogurts, sauces, processed fruit snacks). Their structures consist of greater than 90% water and so careful drying is needed to maintain functional structure. This work greatly increased the understanding of microstructure development on drying of these materials and included approaches to maintain quality on drying (mainly freeze drying).

From a process perspective, microwave vacuum drying offers quick and energy efficient drying, (operating under a vacuum maintains quality as low temperatures are used). However, the technology is relatively more complex than traditional methods and requires more careful process design. Work on hydrocolloids has shown microwave drying can maintain functionality before and after drying and rehydration. Similarly preliminary work on supercritical drying developed a unique, low cost lab scale setup that can be used for flexible processing of materials, from drying to extraction. Comparisons were also made between oven-drying, freeze-drying and super critical CO_2 drying, and is was found that osmotic dehydration as a pre-treatment improved product quality i.e. improved rehydration time, and product colour and texture, while reducing the process environmental footprint.

Functional particles

Molecular interactions forming complexes have been utilised to stabilise emulsions, foams and create microstructures for bioactive delivery. These have all been achieved using conventional food grade materials and designed for modulated delivery in physiological environments. Examples of the materials used are fluid gels made from either agar, xanthan or whey protein to stabilse foams, and modified lubrication properties for improved mouthfeel. Hydrophobic modification of kappa carrageenan fluid gels has also provided improved foam stabilisation, and potato protein isolate/ kappa carrageenan complexes for emulsification.

Starch particles have also been utilised in double emulsions for ‘programmed’ breakdown in the mouth for sodium reduction in emulsion based foods. The physical properties of the starch particles were modified by octenyl succinic anhydride (OSA) treatment and during oral processing native salivary amylase hydrolysed the starch and destabilised the o/w emulsion releasing the inner w/o phase and subsequently sodium into the oral cavity, resulting in a salty taste. Levels of OSA modified starch were optimised for sodium delivery and the results demonstrate a promising new approach for the reduction of salt or sugar in emulsion based foods. The addition of OSA modified starch (0e5wt%) to (EWP) foams has also been shown to enhance foam stability by up to 1200% without compromising the foaming capacity, mainly due to a hypothesised exclusion volume effect.

Particulate xanthan (made through either extrusion of spray drying), when compared to its polymeric counterpart have also been shown to provide better in-mouth dispersion, which can lead to both salt and sugar reduced foods, due to better mixing properties in the buccal cavity, delivering tastants in a more effective way.

New functional materials have also been explored. Spherical particles made from waxes have shown exceptional foaming properties and allows the incorporation and stabilisation of gas bubbles that can further reduce the calorific density of foods.

Insects are seen as a potential source of protein for future generations, but the understanding of the proteins and their capability to provide functionality in foods akin to those from more conventional materials is still in the early stages of exploration. Work has been undertaken in the CIM to identify the interfacial and emulsifying properties of mealworm protein at the oil/water interface.

Particle stabilised interfaces are often termed to be 'Pickering' stabilised. The quest to identify and use bio-based particles with a Pickering stabilisation potential for food applications has lately been particularly substantial Work in the CIM has progressed the understanding of food grade 'Pickering' particles. Materials used to explore such opportunities have included the creation of lipid-based particles, the use of natural waste materials (linked to the next theme below), and in a novel way nanonization technology has been used to create curcumin Pickering particles.

Solid lipid particles have been manufactured via melt-emulsification and subsequent crystallisation and shown to stabilise oil-in-water (o/w) emulsions against coalescence where emulsion stability could be achieved when low amounts (0.8 wt/wt%) of a surface active species (*e.g.* Tween 80 or NaCas) were used in particles' fabrication. Interfacial behaviour was closely linked to the type and concentration of the surface active component used. Emulsion droplet size was controlled by varying several formulation parameters, such as the type of the lipid and surface active component, the processing route and the polarity of the dispersed phase. Dissolution of lipid particles in the oil phase was observed and evolved distinctly between a wax and a triglyceride, and in the presence of a non-ionic surfactant and a protein, yet this behaviour did not result in emulsion destabilisation. Moreover, emulsion's thermal stability was found to be determined by the behaviour of lipid particles under temperature effects where the types of lipid and amphiphilic agents employed were found to affect lipid particle thermal behaviour the most.

Aqueous dispersions of tripalmitin particles have also been produced (with a minimum size of 130 nm) *via* a hot sonication method, with and without the addition of food-grade emulsifiers. Depending on their relative size and chemistry, the emulsifiers altered the properties of the fat particles (*e.g.* crystal form, dispersion state and surface properties) by two proposed mechanisms. Firstly, emulsifiers modify the rate and/or extent of polymorphic transitions, resulting in the formation of fat crystals with a range of polarities. Secondly, the adsorption of emulsifiers at the particle interface modifies crystal surface properties. Such emulsifier-modified fat particles were then used to stabilise emulsions. It is proposed that the stability of the emulsions was additionally enhanced by sintering of fat particles at the oil–water interface, providing a mechanical barrier against coalescence.

The functionality and functionalisation of waste particles as an emulsifier for oil-in-water (o/w) and water-in-oil (w/o) emulsions has been demonstrated. Ground coffee, cocoa and brewers' spent grain waste have been functionalised, due to their naturally high lignin content, which has been shown to be the component imparting emulsifying ability. The waste particles readily stabilised o/w emulsions and following hydrothermal treatment adapted from the bioenergy field they also stabilised w/o emulsions. Refinement of the hydrothermal treatment and broadening out to other lignin-rich plant or plant based food waste material are promising routes to bring closer the development of commercially relevant lignin based food Pickering particles applicable to emulsion based processed foods ranging from fat continuous spreads and fillings to salad dressings.

An antisolvent precipitation technique was used to fabricate the curcumin nanoparticles. For the whole process only materials and solvents that are acceptable to use in the food products were used e.g. curcumin, sunflower oil, ethanol, whey protein. After nanonization, native crystalline curcumin particles were converted into amorphous, nanosized particles of 220 nm able to stabilise O/W emulsions with an initial droplet size of 1.2 µm, which remained stable for 30 days at 4^{o}C.

Controlling food material properties utilising solvent quality

The research has investigated how changing the solvent quality, including using salts, sugars, alcohols, the acid/basic environment and ionic liquids influences the structuring process of gelling agents in an aqueous environment. This has led to an increased understanding of molecular gelation mechanisms, has input into the pre-treatment of materials for drying and rehydration (discussed above) and, in part, resulted in a patent application.

In the case of alcohol, the solvent effect on the gelling agent (kappa carrageenan and gellan gum) is evident, leading to structure shrinkage and distortion due to a high-induced stress on the gel network. Gradual addition of the alcoholic solution was found to considerably reduce this behaviour due to the slower solvent exchange.

A comparison of the texture of wet gels prepared in acid and basic conditions showed that decreasing the pH of the gel to the pKa resulted in an increase in the gel strength and the Young's modulus. On further lowering the pH, both properties decrease dramatically. Post-gelation exposure to water and basic solution led to a reduction in mechanical properties, whereas exposure in acidic conditions resulted in gels with increased strength. To further understanding the effect of starch granule dissolution in NMMO, following from similar work in the area of cellulose dissolution, basic conditions have shown starch to ‘gelatinise’ at room temperatures. In the case of NMMO, an anti-solvent exchange showed starch to be trapped in an amorphous state, thereby a similar effect will be explored for a neutralisation of ‘cooked’ basic starch.

Research has also investigated how temperature set hydrocolloids (such as carrageenans and gellan) could be structured at 30^{o}C. A new method has been developed for forming hydrocolloid gum structures, which have the rheological behaviour of a hydrocolloid fluid gel, but without needing to process at high temperatures. These structures have been used to stabilise emulsions and double emulsions for significantly longer periods of time, compared with the corresponding formulations where the gums were not present. This has also resulted in a patent, which highlighted both the novel structures, and the low energy processing which was developed during this research.

Emulsions with low energy input

Two areas have been focussed on in developing low energy input emulsions, namely Confined Impinging Jets (CIJ) and Rotating Membranes.

A simple and effective approach for producing highly stable, submicron sized, oil-in-water emulsions by high-shear, controlled turbulence in a confined impinging jet mixer using commercial-grade components and low molecular weight emulsifiers has been investigated. Physiochemical effects of small molecule emulsifiers or surfactants and their formulations on drop breakup and stability were found to be important and were investigated to determine the optimal emulsifier deployment strategy. The mixer was easy to fabricate and operate, and several mixheads schemes were designed and tested for enhancement of local turbulence within the mixing volume. There is ample evidence that the confined turbulent impinging jet mixer can accelerate the development of specialized emulsion-based products/applications by providing a robust platform for synthesis of submicron and nano emulsions with precise properties at industrially relevant scales.

Rotating membranes are a relatively new technique, where the shear stress is generated by the rotation of the membrane and the to-be-dispersed phase passes centrifugally through the pores of the membrane and forms droplets moving into the continuous phase. The effects of using different membrane materials and morphologies in the membrane emulsification process were observed using similar operating parameters and system geometry, allowing a direct comparison of not only the membranes themselves but also between both a stationary cross-flow membrane emulsification device and a rotated membrane emulsification device. Each membrane type tested had distinct characteristics, and the droplet sizes produced responded differently to changes in operating conditions. The rotating membrane produced similar droplet sizes to the cross-flow membrane system, but at a much lower shear rate. The Shirasu porous glass(SPG) membrane produced the smallest droplet sizes (<1 µm from a 1 µm membrane), however the stainless steel membrane produced the lowest droplet size to pore size ratio (~0.5:1) due to its cylindrical pore geometry as opposed to the tortuous geometries of the other membranes used. The emulsion droplet size: (i) decreased with increasing rotational velocity (RV), due to higher detaching drag force acting on the droplets, and (ii) increases with increasing trans-membrane pressure (TMP), due to higher interface formation rate. The emulsion droplet size increased as the viscosity of the continuous phase was higher. When the RV increases, the viscosity of the shear-thinning solutions reduces and the role of advective transport increases, aiding interfacial tension decrease and the production of small droplets. The used of functionalised particles in stabilising the emulsion droplets produced via this approach has also been explored. Rotating membrane emulsification has properties with potential to produce shear sensitive emulsion microstructures with small droplet sizes. Emulsion microstructures such as duplex emulsions, core/shell structures beads etc. can be used in the production of novel food structures.

Air as an ingredient

Air inclusion in products, as an added ingredient is relatively new, and thus far has been confined to enabling salt reduction (SODA-LO®, Tate & Lyle's Salt Microspheres) and sugar reduction in chocolate (Nestle). The work carried out in the CIM has focussed on two technologies, spray drying, to produce hollow particles, and aerogel formation using freeze-drying.

The research concerned with encapsulated air microparticles by spray drying technology is to create a new food ingredient, particularly aimed at the manufacture of foam based products. As such air would be added as an ingredient cutting out conventional whipping processes enabling process minimisation and novel product development. The microparticles need to retain their microstructure during incorporation into the food matrix and subsequent processing steps, until the particles and thus the air is kinetically trapped. Contact with media leading to particle hydration and potentially untimely particle collapse is inevitable necessitating tight control of the particle wetting properties, for example via addition of surface active components. Unfortunately, their presence critically affects the morphology of particles. Here the influence of gum Arabic (GA) as amphiphilic functional hydrocolloid on the physical properties has been investigated, probing the microstructural development and the distribution of elemental components in the microparticles. Particles of spray dried Maltodextrin-GA were spherical shape without apparent breakage with a smooth surface and were hollow. The surface of the spray dried particle were dominated by GA as characterised using X-ray photoelectron spectroscopy.

Aerogels can be produced from inorganic sources, most frequently silica, and organic sources, which are gaining more interest due to their renewable and biodegradable properties. Solutions of food grade viscosifiers (fenugreek (FG), locust bean gum (LBG) and Methylcellulose (MC)) including dispersed cellulosic fibres were prepared and freeze-dried. Texture, microstructure and moisture uptake at ≈2%, 43% and 97% relative humidities of the foam samples were tested. Compression tests showed that FG required the least force to compress the foam to a true strain value of 0.4 and LBG foams resulted in the highest Young's Modulus, but this was not statistically significantly different from MC. This indicates that cryogelation of LBG is not the only factor influencing foam integrity perhaps with structural differences between MC and FG also influencing the result. In all foams the addition of cellulose fibres increased bulk density and mechanical strength. Moisture uptake results identified that the MC foam had improved ability to withstand high RH, measured by height loss and further compression tests, and for all foams the addition of cellulose fibres improved the stability. MC exhibited hydrophobic properties when exposed to cold water and gelled when immersed in hot water. Therefore, aerogels can be designed and tuned for addition into cold and hot aqueous foods.

Future plans

The work highlighted above spans TRLs, but is very much focussed on developing the fundamentals. There has been some industry pick up, but there needs to be a further push on all fronts to create that technological pull through. Some of that will be aided by computational modelling, now that some of the fundamentals are in place, allowing further optimisation of both process and ingredient / microstructure space.

Upgrading of ingredients for improved resource utilisation

Work has been undertaken to deliver against the initial plans of delivering food manufacturing process innovation utilising natural structuring ingredients. Materials which have been the focus of research have included pea haulm, oil seeds, brewers' spent grain, rice bran, oat husk, potato waste and mixed vegtal mass. This has involved process innovations in order to functionalise the materals. The following examples indicate the progress made, and has involved collaboration with Unilever, Cargill, Nestle and PepsiCo. Associated projects have also impacted on Branstons, the Green Pea Company, Molson Coors, Campden BRI, McCain Foods, New Food Innovation and Chingford Fruits. Extended academic collaborations also include University of York and the Indian Institute for Food Processing Technology.

Connection between the CIM and Centre for Sustainable Energy Use in Food Chains in a project entitled 'Transformation of food processing by-products into value added products', involving Brunel University and the University of Reading.

Themes:

- Recovery of natural materials
- Waste valorisation
- Fat reduction
- Clean label emulsifiers

Protein products from brewers spent grains (BSG)

Spent grain is a major by-product from the brewing industry, which consists of the wet solid material remaining after the mashing process, after the majority of starch and soluble sugars have been extracted from the malt prior to fermentation of the wort liquor. Several hundreds of thousands for tonnes of BSG are produced by breweries in the UK annually, which are sold primarily as a low-value ruminant feed. The nutritional content for feed applications is acceptable, where typically BSG contains around 25% protein and around 60% polysaccharides on a dry basis. However, as-made wet BSG consists of only 25-30% solids after pressing, which not only lowers deliverable nutritional value but also leads to microbial instability resulting in a low storage life of maybe 2-3 days. Protein and 'flour' rich in protein have been extracted utilising a range of different extraction, purification and separation technologies, and the materials used in concept food products. The work has led to a major internal research focus within the organisation of one of the major food and drink companies.

Protein concentrates from potato by-products

Potatoes are grown commercially on a large scale, either for direct use as a vegetable dish, or for further processing to manufacture products such as fries, mash and snacks. Additionally, the crop is utilised as a feedstock for production of starch, as used as a food ingredient or for industrial applications. The potato tuber consists of flesh comprised of cells containing multiple starch granules, which are surrounded by the cell cytoplasm, bounded by a thin cell wall comprised of polysaccharides including structural cellulose. The development of new techniques for protein recovery (separation techniques based on ultrafiltration or expanded bed adsorption chromatography have been developed) has prompted investigations to consider whether waste or low-grade potatoes from crop harvesting and sorting might also be processed to separate out a protein concentrate as an added value bi-product. Whilst endeavours are made to reduce spoilage and to maximise the proportion of grade 1 crop, inevitably a significant proportion of the crop is down-graded and is either sold as animal feed as stock potatoes or is sent for anaerobic digestion. Processes may be considered where the sub-grade feedstock is macerated as in starch production, and where a simpler centrifugation step allows separation of juice from the remaining starch containing flesh, which would still have value for anaerobic digestion. The protein containing juice can then be further processed using ultrafiltration or adsorption chromatography to extract a protein concentrate. These technically elegant solutions retain the protein in the native state, allowing it to be spray-dried and hence delivering properties such as foam formation, stabilisation and emulsification when rehydrated as a food ingredient.

Fibre materials from pea-haulm

Peas are grown widely as a commercial crop in the UK and in other countries, where the varieties vining peas have been bred to assist large-scale mechanised agricultural practices. The crop can be harvested using sophisticated mechanical harvesters, something like a combine, which collect up the entire plant and then split the pods and separate the peas by a combination of mechanical and centrifugal action in the harvester body. This efficient method allows the peas to be taken away at intervals by accompanying trailer and where in some businesses they are then shipped directly to freezing plants to ensure maximum freshness.

The crushed green material from the empty pods and the rest of the plant is dropped from the rear of the harvester back onto the field, to be ploughed in for the next crop. Whilst some retention of green biomass generated is required for soil quality it is likely that a least of a proportion of this residue would be available for separate collection and processing for other feed and food applications. One possibility is to juice this whole material, for example using an industrial screw press, to separate out a green juice fraction, leaving a comminuted pulp material as a further residue. The green juice has considerable potential as a nutritional ingredient, with a high concentration of protein and essential vitamins and oils and minerals, which could be spray or freeze dried to give a stable powder product. The residual pulp has a fibrous texture, consisting of stem, leaf and pod structural tissues of the plant, also containing some protein and useful micronutrients, which has potential as a dietary fibre product. However, in its as-produced state the residual pulp is likely to have poor sensory texture and further processing would be required to reduce particle size to a level where any grittiness or stringiness sensation is lost. Wet and dry milling has been carried out in the quest to functionalise the material, along with chemical extractions and the outcomes have been very promising for the creation of low energy density foods.

Valorisation of fractions from agri-residue feedstocks for micro nutrients

Green field residual is referred to the green leaves, vines, part of plants and grass left behind the harvesters. Millions of tonnes of green haulm/residuals are generated from agricultural production every year in the United Kingdom. The green residuals from various plants have been reported to contain a wide range of valuable macro and micronutrients, much of these are concentrated in an abundant organelle called the chloroplast. The recovery of chloroplasts from green food waste leads to increased nutritional content per unit mass as compared to the fresh leaf. The derivation of nutrient rich particulate fraction from green biomass is simple and has real potential to provide functional ingredients to food and feed. Chloroplasts are a type of plastid organelle found in plants cells; they produce energy via photosynthesis. It is in the chloroplast that major part of plant's vital nutrients are made. By structure, chloroplasts are lens-shaped bodies with a diameter of approximately 5-10 µm. An innovative procedure for plant chloroplasts isolation has been developed to use chloroplasts as functional food/feed ingredients. The method is simple and environmentally friendly. It is based on juice extraction by physical fractionation from green plant materials and recovery of its chloroplast-rich fractions (CRF) by centrifugation. Major (total lipids, proteins, ash and carbohydrates) and minor nutrients (omega-3, β-carotene, lutein, α-tocopherol and ascorbic acid) of the biomass from pea vines straw have been concentrated using this physical method. Results show that the CRF recovered from fresh pea vine straw/haulm consisted of a number of essential micronutrients such us, α-linolenic acid (C18:3n-3), β-carotene, lutein and α-tocopherol.

Another recent study also explored the nutritional composition of CRF extracted from various green biomasses. Findings indicated that, on a dry weight basis, CRF material from a range of green biomass was enriched in a range of micronutrients. Vitamins E (α-tocopherol), pro-vitamin A (β-carotene), and lutein were all greater in CRF preparations as compared to their original leaf materials. Of the minerals, iron was most notably concentrated in CRF. The study concluded that CRF consisted of higher concentrations of essential micronutrients such as, α-tocopherol, β-carotene, lutein, α-linolenic acid (C18:3n-3) and trace minerals (Fe and Mn) compared with their original leaf materials on dry weight basis. CRF could be used as a concentrated source of nutrients in food/feed formulations.

Recovering nutritionally-rich fractions of chloroplasts from field green residuals / green waste biomasses could create new sustainable and functional food ingredients, enriched with essential micronutrients, which is in theory more bioaccessible than nutrients in chloroplasts enclosed by a cell wall. This approach may provide a way to ensure that poorer societies have access to food rich in valuable micronutrients. In addition, there could be a range of commercial opportunities to use isolated chloroplasts in food and feed formulations.

Valorisation of fractions from agri-residue feedstocks for waxes

Several types of agricultural residues and vegetable by-products resulting from food manufacture are receiving growing attention as sources of valuable functional molecules. The bran removed from cereal kernels (rice, wheat, and oat), seeds left from juice production, date palm, and maize germ are only few examples of by-products where lipids represent a relevant fraction. These lipid compounds are or could be exploited to satisfy different market demands: nutraceutical supplement (omega-3 oil and lipophilic vitamins supplements), nutritional (edible oils from rice bran and maize germ), coatings (waxes), animal feed formula ingredients. Among the lipids of industrial interest, plant waxes represent a relatively small fraction (by weight) of the waste biomass but with great potential to be re-integrated into the supply chain as high-added value chemicals and materials. This is primarily because plant waxes offer a suitable alternative to petroleum based waxes. This technological functionality together with consumers' preference for sustainable and natural plant products in healthcare and cosmetic applications, has determined a growth in the commercial demand of natural plant waxes over the last few years. A parallel stream of research with great potential for wax exploitation is the "oleogelation". This has emerged in the last decade and aims at using waxes in food applications. The word "oleogelation" refers to the use of non-triglyceride molecules to create lipid gels, referred to as "oleogels". Oleogels are gels where the continuous phase is an edible oil (olive, soy bean, sunflower, etc.) as opposite to "hydrogels" where the continuous phase is aqueous in nature. It has been shown that various plant waxes are effective oleogelators since they are required in small amounts (from as low as 1%, wt%) to produce self-standing gels. From a colloidal point of view, wax molecules form a continuous network of interconnected crystals immobilising the oil thus providing it with a solid-like consistency. The morphology of the crystals, their ability to immobilise the oil, and the overall consistency of the gels depends on the type of wax and on the process adopted to form the oleogels. Unpublished work carried out in our laboratories has demonstrated that the cooling rate affects the size of the crystals in rice bran wax (RBW) based oleogels. RBW is a by-product of rice bran oil production (an oil produced from rice bran) and is an approved additive in foods (E908). RBW is known to form crystals that appear as bright needle-like particles when visualised using polarised light microscopy. Micrographs in Figure 2 show the microstructure of two oleogels containing 2% RBW in rapeseed oil and formed applying different cooling profiles. It can be clearly noticed that the cooling rate significantly affects the size of the crystals: when formed under rapid cooling (Fig. 2a) crystals are significantly smaller than those formed under slow cooling profile (Fig. 2b). Wax based oleogels have also been successfully applied in baked products demonstrating to be a valuable alternative to saturated and *trans*-fats but more research is needed in this area.

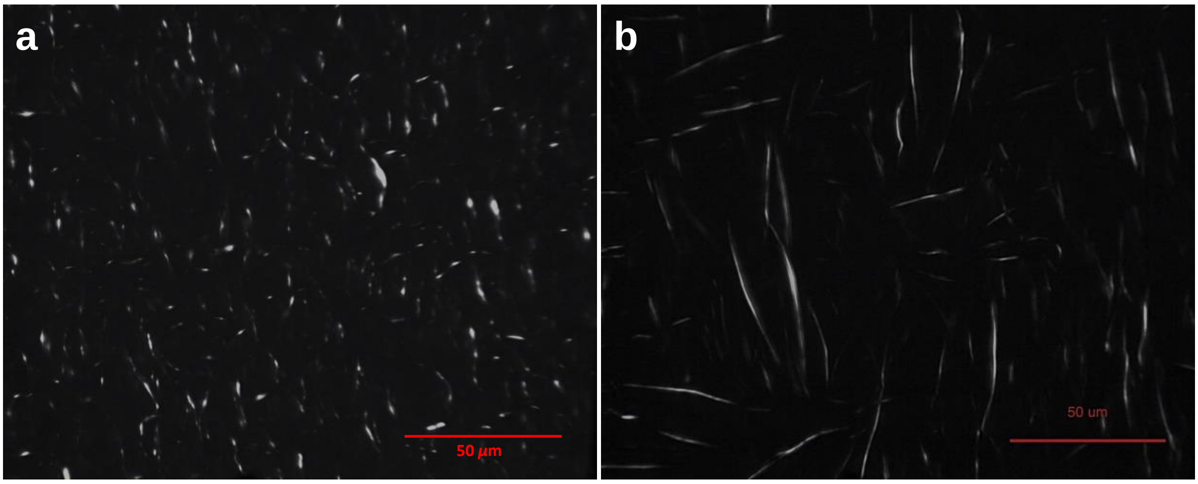

Figure 2: Microstructure visualisation of 2% RBW oleogel in rapeseed oil. Crystals appear as needle like particles. (a) Rapid cool, (b) slow cool.

Waxes are ubiquitous plant materials given their physiological functional role. Therefore, there are virtually an infinite number of combinations which could be engineered to offer new sustainable solutions to deliver innovation using waxes obtained from agri-food by-products. These biomaterials could be used to replace saturated and *trans*-fats in foods as well as petroleum based waxes in healthcare and cosmetics.

<u>Lignin-based food ingredients: utilising food waste</u>

Research in the CIM on lignin-based food ingredients built on work undertaken in the period leading up to its foundation. This previous research focused on building scientific knowledge behind the natural emulsifying ability of cocoa particles in order to facilitate the identification of other natural food particles with emulsifying ability. Borrowing processing and analytical methods established in the bioenergy field, and extraction methods for food components, we were able to establish that the presence of lignin in the food particle promotes its emulsifying functionality. Food particles of negligible fat content were also able to stabilise aqueous based foams. Lignin is a hydrophobic polymer providing structural stability to plant cell walls. It has three monomer units and composition in the plant cell wall varies with development stage and botanical origin, e.g., soft wood and hard wood differ.

The CIM enabled us to test the hypothesis that other lignin-rich materials, focussing on food waste and by-products of manufacturing processes, also possess emulsifying ability. In order to develop clean label emulsifiers, or hydrophobic microparticles, to be applied as zero calorie filler particles in fat continuous product matrices for fat reduction, we have worked with Campden BRI and Mondelez, as well as groups at the University of Nottingham which have particular processing (Chemical Engineering) and analytical (Chemistry) expertise. We have made it our priority to work with processing media applicable to the manufacture of food ingredients, and to build understanding of the material properties of our feedstocks in order to evaluate whether in the food industry widely established processes would be applicable for conversion into emulsifying particles, to enhance the economic viability of this waste valorisation proposal.

We have taken two approaches in this research:

Process-induced modification of lignin-rich biomass: Our initial activity in this approach focussed on affirming the role of lignin as the hydrophobic particle component imparting emulsifying ability. It had been suggested that the lipids present in cocoa material was contributing or even necessary, which we were able to disprove (original research, deepening scientific insights as CIM research. Hence, it suggested itself to borrow subcritical water processing from the bioenergy field and apply to our materials to "relocate" the lignin trapped in the cell walls to the surface of the food particles. During this process, lignin melts, protrudes to the surface of the feedstock particle and upon cooling, as it is hydrophobic, it deposits as droplets onto the particle surface. We hypothesised that this processing step renders the particle surface sufficiently hydrophobic to enable stabilisation of water-in-oil emulsions, as opposed to oil-in-water emulsions which were readily stabilised by the untreated feedstock. Selecting ground coffee waste as an easily accessible alternative feedstock to cocoa material, to validate our hypothesis that presence of lignin is the only feedstock requirement for the applicability of this waste stream valorisation route, we have demonstrated that following subcritical water processing the particles indeed stabilised water-in-oil emulsions, although the droplets were larger than relevant to fat continuous emulsion-based foods such as margarine or confectionery fillings (CIM research). Based on these scientific insights, and the fact that droplet size in particle stabilised emulsions relates to particle size, and particle hydrophobicity relates to surface coverage with lignin, a PhD project, funded by the University of Nottingham (School of Biosciences and Faculty of Engineering) and Campden BRI, on the process-induced modification of lignin-rich biomass started 2016. The overall aim of this PhD research is to develop the underpinning science for the targeted process-induced modification of lignin-rich biomass into emulsifying particles, with particular focus on developing water-in-oil emulsifiers stabilising sufficiently small emulsion droplets to be applicable as fat reduction concept in foods such as spreads and confectionery fillings. The PhD student selected to work with Brewers' Spent Grain (BSG, 12-28% lignin). Alongside the process development, an NMR method to quantify the composition of the lignin droplets on the particle surface, following extraction with ethanol, is under development. We can report that subcritical water processing above the melting temperature of the lignin in the BSG mobilised the internalised lignin to the surface of the particles, as confirmed by solid-state NMR analysis of the surface-adhering droplets. Droplet size ranged between <1 and 15 microns in diameter depending on processing conditions. Hydrothermal treatment and delivered processing conditions. Water-in-oil emulsions with droplet size between 50 and 400 microns were stabilised, which is still an order of magnitude larger than required to stabilise fat continuous food emulsions. Hence, the design of a pre-treatment step to generate functional particles of much lower particle size is subject of the final stages of this PhD research.

Generation of lignin-rich microparticles following biomass extraction: To overcome the limitations of feedstock particle size, we took to designing microparticles from lignin-rich biomass extracts as the research topic of another parallel PhD, funded by The University of Nottingham (School of Biosciences) and Mondelez. The PhD student selected cocoa particles as her feedstock and applied solvent extraction, following subcritical water processing or acid-assisted solvent treatment to increase lignin yield. Lignin-rich solvent extracts were then converted into microparticles and their ability to stabilise emulsions demonstrated. She has demonstrated the stabilisation of smaller emulsion droplets as the advantage over emulsifiers produced with approach (i).

There are two key developments arising from this work. The first confirms that lignin can contribute to fat reduction for popular foods by acting as an emulsifier. The second contributes to the increasingly important issue of recycling wastes and by-products of industrial food production processes.

Firstly, a preliminary study was undertaken to demonstrate that low fat (< 1%) cocoa particles allowed the removal of fat or egg from a cake formulation whilst still maintaining an aerated structure and a springy texture (outlined below).

Secondly, the scientific understanding of how to create functional food particles from lignin-rich waste that provide food structures comparable or superior to existing structuring ingredients was significantly advanced during the funding period of the CIM. It provides the foundation of a currently advertised PhD studentship. With regard to exploitation in industry, feedstock testing for heavy metals is underway with Mondelez and Campden BRI is assisting interested members with questions that arise around the novel foods legislation and these systems.

Future plans

The work has scratched the surface of the abundance of opportunity in better utilising natural materials, and in most cases materials which are discarded as waste. It is better to describe these materials as untapped 'resource', and future research is required to follow through the impact of such findings, particularly in the emphasis on 'clean growth' outlined in the Industry Strategy White paper, enabling a more efficient use of resources in a more resource efficient (bio)economy. This will mean creating a 'circular economy' view for the industry, requiring agile manufacturing innovation to functionalise the raw materials around us to provide ingredients of the future for the food and parallel industries.

Food manufacturing for healthy diets and lifestyles

Research carried out at the CIM has involved and impacted on a range of multinational food companies, including Unilever, Cargill, PepsiCo, Rich Products, Bakkavor, Diageo, as well as consumers themselves. We have worked with industry to engineer a novel series of healthier foods, utilising the knowledge developed further in the research work carried out in the CIM.

Themes:

- Reduction of fat, sugar, salt
- Increase protein, fibre
- Microstructures for delivery

Fat-reduction in emulsions

The science underpinning these novel foods is the microstructure engineering of soft solids. We developed a fundamental mechanistic understanding of emulsion behaviour in flow. This allowed us to control the local physics in order to use phase inversion in the production of fat-continuous products with as little as 10% fat phase. We provided our industrial partners with the detailed understanding of the role of structuring agents and the kinetics of phase changes required to undertake these processes. This knowledge allowed process engineers to position crystals at droplet the interface and to therefore control droplet breakup and re-coalescence. Because the crystal position in the interface of droplets (Pickering emulsions) makes them inherently more stable in storage whilst also enhancing coalescence in flow, food manufacturers were able to economically produce stable fat-continuous emulsions at fat content levels which were inherently more stable if water continuous (> 50% water). These structures are kinetically trapped as a result of the crystals in the interface, thereby enabling an enhanced flavour release to achieve the desired oral properties upon consumption in spite of the reduced-fat content of the food. Maintaining maintains taste and texture is essential our industrial partners maintaining their sales in a competitive global market.

In addition, our research developed ways to control the relative viscosities of the two phases in emulsion products. As oil's viscosity is fixed (edible triglyceride oils) this required research on the use of hydrocolloid physical chemistry to structure the aqueous phase during processing. This is a complex issue as the hydrocolloids also impact on sensory properties of the final product. The research thus aimed to control both in process and on consumption parameters separately. Developments in understanding the structuring of Oleogels (described above) have enabled the control of oil structuring in oil and water continuous products, and has been utilised in the case study outlined below.

In summary, the research carried out at the CIM allowed industry to induce a self-catalytic inversion process by controlling and manipulating crystals at the oil/water interface. Because of this research, inversion can now be temperature controlled (not time controlled) thus enabling rapid inversion (the process runs at 10 tonnes/hour resulting in short residence times requiring control and manipulation of the kinetics of the material phase changes) and continuous production of low and very low-fat spreads. This work was led by Professor Norton's group, along with Spyropoulos, Mills, Pelan, Wolf, and the researchers at Nottingham, including Foster, di Bari and Gould.

The impact of this research has been to enable food manufacturers to develop and market a greatly expanded range of low fat-foods, contributing to measures to reduce fat, sugar and salt consumption as well as generating substantial sales and profits in this key economic sector. This is of fundamental importance as the links between diet, obesity and ill-health have been well established and form a major element of public health advice in the UK and elsewhere.[1] The wider availability of attractive low-fat options in a growing range of everyday foods has helped consumers follow healthy eating guidance.

There is evidence that healthy eating is taken seriously by consumers; for instance, survey results included in Defra's most recent annual summary of food-related data reported that nutritional content is highly influential on shoppers' purchasing decisions, in particular the level of fat within the food (33% of shoppers). Of people asked what they were doing to obtain or maintain a healthy lifestyle, 38% said they were eating low-fat versions of food (the third most frequent response).[2] More broadly, these measures bring benefits for society as a whole through helping reduce the incidence and health-related costs of obesity, acknowledged to be a widespread and serious issue.

The findings from research carried out by the CIM have fed directly into the investment in novel manufacturing processes and new low-fat food products by global companies including Unilever, PepsiCo, and Cargill. Researchers at Birmingham and Nottingham have worked closely with these and other companies in long-term partnerships to maximise the impact from their research findings.

This case study clearly demonstrates the importance of the CIM's research in enabling global food companies to address the specific challenge of producing volume-sales food products that have low or zero-fat content whilst retaining the taste and texture required by consumers. As Peter Lillford (Chairman Institute of Food Research, and former Chief Scientist, Unilever) writes: 'the food industry is global and highly competitive. This grouping has international recognition of its research. This is attracting inward investment to the UK. One of the clear targets for Impact'.

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[1] For example, *Obesity: the prevention, identification, assessment and management of overweight and obesity in adults and children*, *NICE Clinical Guidelines*, No. 43 (2006).

[2] DEFRA *Food Statistics Pocketbook 2010*, pp. 39 and 66.

Sugar reduction in cake manufacturing

There is increasing demand from both consumers and the government for food products preserve positive sensorial attributes yet have enhanced nutritional properties. Manufacturing such consumer accepted healthier food products presents a huge challenge for the food industry. Success in product re-formulation requires a deep understanding both of the ingredients' roles and of the processes required to achieve desirable structures.

Within the landscape of rapid product re-design, sugar reduction in foods, as demonstrated by the introduction of the "sugar tax" (6th April 2018), is a top priority of many food manufacturers. Sugar is a key ingredient in delivering acceptable products as it contributes to structure development and stability, and to product weight, volume, flavour, and sweetness. The replacement of this latter functionality of sugars can, to some extent, be considered the easiest to achieve given the availability of a range of sweeteners. However, the possibility of matching the other functionalities requires a combination of approaches and technologies.

A preliminary explorative project carried out by researchers at the Centre, in collaboration with industry, aimed to understand the role of sugar in cakes and investigated innovative formulation routes to successfully reduce its content in sponge. The project also investigated routes to reduce sugar and fat content in frostings. Experiments showed that direct reduction of sugar content by 50% in the sponge would lead to a less developed product with a structure characterised by large holes, considered a structural defect (Figure 3, left cake) compared to a standard cake (Figure 3, right cake).

In Figure 4 details of the structure of the standard (Figure 4a) and reduced sugar (Figure 4b) cake are provided; images are cross-sectional areas, measured by C-Cell. Large holes (in yellow) were present only in the reduced sugar product. The addition of fibres (4%, wt%; Figure 5a and 5b) and protein (10%, wt%; Figure 5c) allowed a 50% reduction in the sugar content, whilst preserving the desired aerated structure and minimising the number of structural defects. Fibres also proved to be a functional structural ingredients in frosting formulations allowing the replacement of 45% sugar producing products with comparable rheological and spreadable behaviour, compared to standard formulated products. Furthermore, the use of rice bran wax oleogels, showed that it was possible to reduce the fat content up to 25% (wt%), without affecting the product quality. This work has demonstrated that fibres, as structural active fillers, and proteins, as foam stabilisers, can be used as functional ingredients for the replacement of sugars in cakes obtaining well aerated structures. From an industrial point of view, this work is particularly relevant as it indicates that a deeper micro-structural understanding of the role played by ingredients can lead to healthier products without affecting their quality. Work was carried out in consultation with industry and on industrial formulations.

Figure 3: *Comparison between a standard cake (right hand side) with a 50% reduced sugar one (left hand side).*

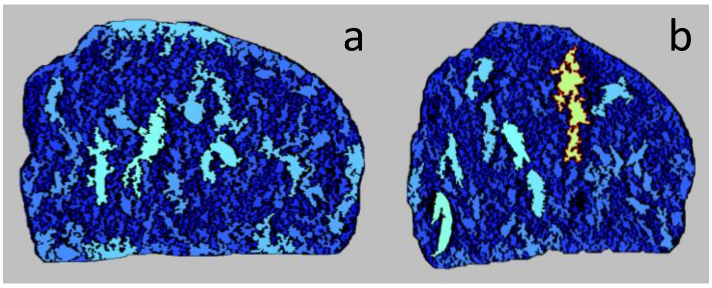

Figure 4*: C-cell cross sectional visualisation of cakes; (a) standard cake; (b) 50% reduction.*

The addition of fibres (4%, wt%; Fig. 3a and 3b) and protein (10%, wt%; Fig. 3c) allowed a 50% reduction in the sugar content, while preserving the desired aerated structure and minimising the number of structural defects.

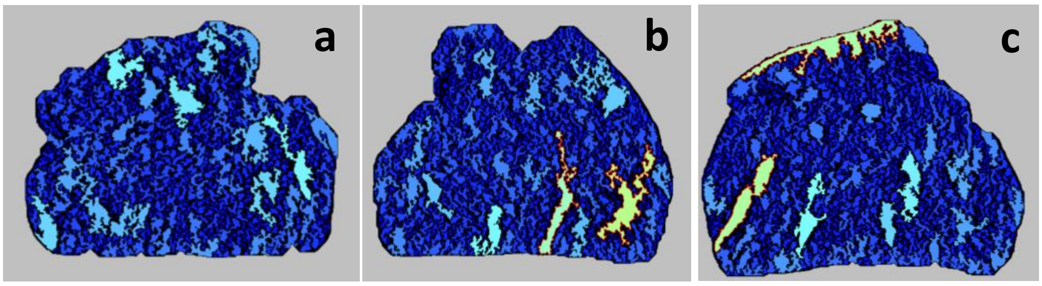

Figure 5*: C-cell cross sectional visualisation of cakes with a sugar content reduced by 50%; where (a) and (b) show replacement by 4% of fibres; (c) replacement by 10% protein.*

Health active delivery

Aside from single active microencapsulation, there is growing interest in designing structures for the co-encapsulation and co-delivery of multiple species. Although currently achievable within solid systems, significant challenges exist in realizing such functionality in liquid formulations. The present study reports on a novel microstructural strategy that enables the co-encapsulation and co-release of two actives from oil-in-water emulsions. This is realized through the fabrication of sodium caseinate/chitosan (NaCAS/CS) complexes that in tandem function as encapsulants of one active (hydrophilic) but also as ("Pickering-like") stabilizers to emulsion droplets containing a secondary active (hydrophobic). Confocal microscopy confirmed that the two co-encapsulated actives occupied distinct emulsion microstructure regions; the hydrophilic active was associated with the NaCAS/CS complexes at the emulsion interface, while the hydrophobic active was present within the oil droplets.

Aided by their segregated co-encapsulation, the two actives exhibited markedly different co-release behaviours. The hydrophilic active exhibited triggered release that was promoted by changes to pH, which weakened the protein−polysaccharide electrostatic interactions, resulting in particle swelling. The hydrophobic secondary active exhibited sustained release that was impervious to pH and instead controlled by passage across the interfacial barrier. The employed microstructural approach can therefore lead to the segregated co-encapsulation and independent co-release of two incompatible actives, thus offering promise for the development of liquid-emulsion-based formulations containing multiple actives.

Future plans

The work carried out has built upon a solid foundation of world leading research in the UK. In 2014 the KTN presented a White paper 'Redesigning the food supply chain: choosing and producing healthy, nutritious and sustainable food' with a vision for 'Making healthy foods more pleasurable and pleasurable foods healthier'. As UKRI refocuses on key national challenges the provision and acceptance of healthier foods, particularly for the most vulnerable parts of society, remains a key area of science and technological challenge. The work progressed within the CIM should provide a major input into the next phase of developing a 'Healthy Nation'.

Novel liquid formulations that allow for the independent co-delivery of multiple actives. Formulations that currently allow for co-delivery of multiple APIs (relevant to combination therapy) are mainly (if not exclusively) in solid form (e.g. tablets). New work is required which will focus on liquid pharmaceutical formulations which are more relevant to paediatrics. Innovative microstructural approaches that enable the encapsulation and delivery/release of both hydrophilic/hydrophobic actives within/from simple o/w emulsions will be design.

New flexible manufacturing processes

It is envisaged that increases in productivity will require much more agile and flexible food production capabilities. This has been re-emphasised in the new vision highlighted earlier in this report. The initial thoughts in the construction of the CIM bid was that drop by drop production for tailored emulsion products, better control of the machine-product interface, microfluidics for complex food emulsion production, and membrane emulsification production of shear sensitive structures would be the direction of the research. Three of these areas have been discussed in the section 'New Processing Technologies (above), while the area of 'machine-product interface' has focussed on the development (in the time of the CIM) of 3D printing for food and sensing for cleaning. If the extreme of flexible and agile processing is to produce a product at an individual level (n=1; where personalised nutrition is becoming an increasingly popular opportunity), 3D printing needed to be explored. Common technologies that have been developed have been creating products such a paste-like textures, while we set ourselves the challenge of tackling the control at the molecular level, developing 3D printed microstructures using Fused Deposition Modelling, Binder Jetting and High Viscosity Jetting.

Working in collaboration with Martec and colleagues in the faculty of Engineering (UoN), researchers at LU have developed sensing capability for optimised clean-in-place.

Themes:

- 3D printing
- Sensing for cleaning

Fused Deposition Modelling

The printability of mixtures of gelatin and kappa-carrageenan were investigated, involved designing and developing a new print head for an extrusion based additive manufacturing process in order to print edible materials which undergo a phase transition. Design rules were established to determine whether the materials fit the requirements of the process. The gelling temperatures of the systems (24–42 °C) and the rheological characteristics including: flow profiles, evolution of elastically dominated structures and frequency dependent behaviour, were established. The mixtures were subsequently printed at two temperatures, just above and much greater than, their gelling temperatures. Analysis showed rheological behaviour accompanying the coil-helix transition were key to printing the product in a well-defined manner. The printing fidelity was related to the magnitude of the storage modulus, which needed to be greater than 23 kPa, as well as the rapid formation of an elastic network, recovering at least 73% of the maximum storage modulus within 200s.

Binder Jetting

Binder jetting is an additive manufacturing technique in which powdered material is sequentially laid down and printed on by an ink binder, in a selective manner, to form a 3D object. In this work we demonstrated the use of a small scale powder layering device under a FujiFilm Dimatix ink jet printer to test prototype powders prior to producing quantities typically used in commercially available binder jetting machines. Design of both food grade powders and ink was required. Powders comprising predominantly of ball milled, amorphous cellulose were successfully used to create 3D structures when interacting polysaccharides were present in the ink (xanthan gum) and as a proportion of the powder component (glucomannan) by inducing selective recrystallization. Requirements for the recrystallization of this powder with a view to structuring have been determined through the control of moisture and thermal energy. The polymer inks were subsequently jetted onto the amorphous cellulose powder to observe powder-binder interactions. These ingredients are categorized as dietary fibre, thus such formulations can be used to create low-calorie 3D printed food designs to be used within food products.

High viscosity jetting

Suspensions of gel particles which are pourable or spoonable at room temperature can be created by shearing a gelling biopolymer through its gelation (thermal or ion mediated) rather than allowing quiescent cooling – thus the term 'fluid gel' may be used to describe the resulting material. As agar gelation is thermoreversible this type of fluid gel is able to be heated again to melt agar gel particles to varying degrees then re-form a network quiescently upon cooling, whose strength depends on the temperature of re-heating, determining the amount of agar solubilised and subsequently able to partake in re-gelation. Using this principle, for the first time fluid gels have been applied to a high viscosity 3D printing process wherein the printing temperature (at the nozzle) is controllable. This allows the use of ambient temperature feedstocks and by altering the nozzle temperature, the internal nature (presence or absence of gel particles) and gel strength of printed droplets differs. If the nozzle prints at different temperatures for each layer a structure with modulated texture could be created. This may also be made possible by printing with 'mixed' fluid gels, where relative particle numbers will be determined by both formulation and processing conditions. This addition will allow for further structure control and multiple nozzles, printing different fluid gel feedstocks which provides an exciting future, whose limits are constrained by imagination.

Work within the CIM on edible 3D printing has allowed the development of equipment, expertise and a flexible set of edible material formulations based largely on what is already use in food processing.

The pioneering work developed in the CIM on additive manufacturing of food has allowed a subsequent multi-partner EPSRC project to be funded aimed at developing a database of future printing materials across a wide range of fields. The project ‘Formulation for 3D Printing’ (Ff3DP) was funded by EPSRC in 2016 as part of the major call ‘Future Formulation’. The project is a collaboration between three universities (Nottingham, Birmingham and Reading) and received contributions from industrial partners (PPG, GSK, Syngenta, Malvern Instruments, Unilever). The programme aims to deliver sector specific libraries of 3D printable materials, develop formulation platforms for multi active delivery, develop formulations that enable control of microstructure and produce a suite of novel materials that can set the direction for formulations for 3D printing over the next 10 years.

Self-optimising Clean-in-Place

The routine cleaning of process equipment within the food and drink industry comes at a large economic and environmental cost. This is primarily due to the time and physical resources required and waste generated. This cost is increased as the majority of Clean in Place (CIP) systems over-clean process equipment for up to 50% of the cleaning cycle as they are unable to determine in real-time when all internal fouling has been removed.

The objective of this project was to develop an intelligent multi sensor network and assess its feasibility to determine the precise level of equipment fouling. These sensors were incorporated within a bespoke lab-scale processing rig and their measurements used to develop the signal and data processing algorithms required for a novel Self-Optimising CIP (SOCIP) technology.

The project has completed and has achieved all original objectives with all Milestones realised within the allocated project timescale. The combined optical and ultrasonic sensor technologies have demonstrated the technical feasibility and identified the key challenges for a next phase of development. The projected operational, energy and water reduction opportunities should lead to significant savings in the industry as cleaning typically represents 30% of the total water and energy use. The communications between the academics and field technical staff has been notable with a well-managed two-way transfer of knowledge and this has been a mutually rich learning experience with a tangible, significant academic REF ‘Impact’ from the project team. The collection and processing of experimental data and presentation of findings has attracted a high level of interest from some major food retailers and volume food processing companies. Greencore, a significant food supplier to Marks & Spencer and Tesco is keen to participate on follow-on projects. Dissemination of results and visibility of the Innovate UK funded project has been highly effective via attendance of project staff at events, seminars and sector technology conferences including a biennial World Congress. Interest has also been expressed from food producers/equipment manufacturers including from USA, France, Germany, Turkey, and Australia. The project has taken guidance from the university enterprise offices to optimise the protection of Intellectual Property Rights. Initially trademarking was formalised, and in the closing days of the project independent IP attorneys were assessing new patent opportunities created from the outcome of the project and preparing a patent filing application.

Future plans

The next step in this process is to capitalise on the specific materials identified in the project to give specific solutions to industry for higher TRL levels, for example in creating personalised drug dosages or bespoke nutritional products for high end sports products. InnovateUK projects on application specific 3D printed future products are currently in development to that end with company partners and collaborators at the University of Nottingham.

The project team are preparing an application for a follow-on project. A SME sensor instrumentation specialist company, Synatel, will join as collaborators to develop the sensors to the stage of full industrial production viability. Greencore have expressed a desire to become a full collaborator offering their manufacturing facilities for production scale prove out and validation of SOCIP to global food manufacturing standards (confirmed in discussions with M&S). The original route to market plan has been enhanced with the Greencore validation trials as a basis of roll out to other food and drink manufacturers several of which have already expressed interest.

Eco-food manufacturing

The sheer size of the food manufacturing sector, the rapid increase in consumption in processed food, together with recent advancement in innovative complex food products driven by ever changing consumer demand has resulted in the food industry to be one of the most resource intensive manufacturing sectors. In addition, because of the shelf life of food products, the inevitable natural wastage of ingredients and the current patterns of global-scale production, distribution and supply have made waste an intrinsic part of food production. This research aims to develop the most appropriate strategies, methodologies and tools for the food sector to maximise resource efficiency in production.

Themes:

- Energy efficiency in food manufacturing
- Water sustainability in food manufacturing
- Waste streams and life cycle impact in food manufacturing
- Consumer waste minimisation

Energy efficiency

The overall aim of this work is to identify new opportunities for improving energy efficiency in food manufacturing and to collaboratively develop viable technical and management solutions for realising improvements.

The process energy consumption of the UK food, beverage and tobacco sector was 29.6 TWh in 2014, 12% of total energy consumption by industry in the UK, and average specific embodied energy was 516 kWh per tonne or 0.5 kWh per kg. The realistic energy savings potential, if supported by relatively strong government policy, has been estimated by different sources respectively at a pessimistic 17% by 2030 across Europe and more optimistically 22% by 2020 in the UK.

This work involves direct engagement with large food manufacturers. A whole system perspective has been used, which takes account of the many inter-dependencies of each element of the food manufacturing system and dependencies on the supply chain and context in which the factory operates.

Potential solutions include:

- Steam peeling: changed geometry and faster heat transfer system => 25% reduction
- Lubes: Synthetic oils 1-30% savings on various food machinery compared to mineral oils
- Flatwire conveyor: 30- 50% stronger than a standard flatwire belt and weighs 10% less than its predecessor
- Industrial Drive: AC-AC matrix design => >90% total harmonic distortion reduction, near unity PF and power regeneration direct to the line. The realisation of the innovation potential would be to create
- Self-sustaining comparative machine-level database to support the power of peer benchmarking in industry – a cycle of data acquisition, visibility and innovation.

Water sustainability

The true cost of water to manufacturers can be up to three times the supply and effluent charges. In addition water shortages, lack of water treatment capacity and ever changing legislation are business risks. In mitigation forward thinking companies have implemented water management policies, but long term sustainable reductions of water consumption in manufacturing can only be achieved through understanding and addressing water use by individual process steps.

The Centre for SMART has developed a set of flexible, non-invasive water analysis instrumentation to monitor in-plant effluent flows across various process steps. The data obtained has been used to develop a **Water Management Framework** to identify hotspots for process or product redesign to improve water sustainability.

The current water sustainability initiatives in industry are focused on pre- or post-manufacturing measures such as rainwater harvesting or improved effluent treatment. Instead the Centre is applying its 4M approach (Measure, Model, Monitor and Manage) to assist manufacturing industry to identify and prioritise process-related water reduction opportunities. In this approach, the water flow among individual production processes is measured, modelled and monitored to provide transparency and insight into water usage and effluent generation within a production facility. A set of instrumentation referred to as MASK (Multi- Analyte Sensor Kit) has been developed, capable of providing real time water content data at the unit process level. The capabilities of the MASK are being characterised and validated using water samples from the food manufacturing industry and validated against standard laboratory based analytical techniques. Data from the MASK will be used to support effective management of water flows within a manufacturing plant and identification of the most sustainable and cost efficient water saving measures.
Manufacturers have little information on water content inside the factory where problems are:

- Exceeding water discharge concerns
- Over/under use of fresh water, *e.g.* cleaning procedures
- Over/under use of cleaning chemicals
- Laboratory analysis of samples is too slow to be an effective management measure

We have investigated the use of optical instrumentation to give in-line rapid analysis to address the problem.

Waste streams and life cycle impact

A systematic framework to increase sustainability performance of food waste management has been designed in this research. This includes a novel food waste categorisation which allows the classification of all food waste types and identification of food waste characteristics necessary to select the most sustainable solution for food waste management, an analysis of food waste management systems and sustainability implications of feasible solutions for food waste management, the development of a food waste management procedure that includes the definition of quantitative attributes and the identification of connections and dependencies amongst attributes, the design of information flows for food waste management, and a scheme to identify optimal calculation steps of attributes. The applicability of the framework has been demonstrated with two case studies completed with UK food manufacturers: a brewery (Molson Coors) and a meat-alternative manufacturer (Quorn Foods). More sustainable alternatives for food waste management were identified, information needed to model their food waste management was analysed and the potential benefits and disadvantages obtained as results were evaluated.

Additionally the work has developed **a system-change approach** from current linear-thinking to an approach that upgrades and re-utilises unavoidable industrial food wastes to create new food products. Food manufacturing is a complex process in which vast amounts of wastes and by-products are generated. An evidence-based whole-system change to recover unavoidable food supply-chain wastes and by-products and use them to produce new food products has been developed.

The following feedstocks have been analysed as a source of functional food ingredients: brewers' spent grain, pea vine waste, out of specification citrus fruits and potato waste (in collaboration with the work on upgrading materials outlined above). Large UK food manufacturers are participating in the project to ensure that the technologies and processes developed in the project are applicable at an industrial scale. Here the work has focused is on waste flow modelling and Life Cycle Assessment (LCA).

Two approaches have been employed:

- Waste flow modelling – to develop a comprehensive understanding and quantification of the amount of food being under-utilised in the industry through the outputs of waste flow modelling. After analysing the reasons for waste generation, initial proactive whole-system solutions to eliminate waste are being proposed and examined, before developing reactive solutions for upgrading the remaining unavoidable waste.
- Life cycle assessment - to assess environmental ramifications of industrial technologies and processes to treat food wastes and by-products. The environmental impact associated with these activities will be compared with existing waste management solutions, which are frequently animal feeding and anaerobic digestion. With this objective, SimaPro software is used to assess the main environmental impacts to air, water and soil.

<u>Consumer waste minimisation</u>

Consumer food waste is a global issue where one third of food produced never gets consumed, revealing a need to promote more sustainable consumption. Interestingly, in the developing countries, 40% of food waste is created in the field and during initial processing, whereas in developed countries, 40% of food waste is generated at the retail and consumption stages. Studies have demonstrated that consumer food waste should not be conceptualised as solely a behavioural problem but rather as a symptom of an unsustainable food system that overproduces, oversupplies, and encourages consumerism. Manufacturers and retailers can play a crucial role in minimising consumer food waste, due to the strategic position they hold in controlling the flow of goods from producers to consumers. It is proposed that bridging the gap between food production and consumption can be achieved through a range of considerations including acquiring a deeper understanding of consumers' needs and demands, incorporating this understanding in various food production and retail activities, and using new advances in information technology to communicate more effectively with food consumers. The study has concluded that Food waste is a global problem but is not homogeneous and that in the developed world, post-consumer food waste is the biggest problem in terms of mass, cost, environmental impact. Reasons for food waste stem from the food provision system, and targeting consumers does not tackle the root of the problem. Targeting the system implies use of a **product service system** (maintain profits by increasing value), which in turn presents challenges to manufacturers, retailers and consumers – however it is believed the problem is solvable, requiring:

- Enabling households to better plan their purchasing and consumption
- Change retail environment and product design
- Relieve individuals from preparation but provide customisation
- Standard offering food (e.g. prepared meals) - Consumer removed from preparation.

Future plans

Linking the work carried out on energy, water and waste management a Resource dashboard is required, utilising digital technologies to create both system and process control. Work is ongoing with companies such as Pukka Pies to make this a reality.

Sustainable food supply chains

The existing food production and supply is based on a global infrastructure that has been developed to satisfy the ever-increasing consumer demand. This has resulted in a huge amount of effort and resources required for the transportation and distribution of food products, which makes the current food supply chains unsustainable in the long-term. In addition recent changes in climate and its impact on resource availability (e.g. varying crop production levels around the world, freshwater shortages and energy blackouts) has highlighted a specific need for the food sector to develop resilience towards volatility in supply levels, and unpredictability in the quality and cost of resources. The ability to manufacture close-to-market using locally grown ingredients and based on distributed manufacturing approaches are some of the key principles that will shape the future of food supply.

Themes:

- Decision support for distributed and localised food manufacturing
- Framework for Enhancing resilience in the food manufacturing sector
- Big data for improving efficiency
- Tools for sustainable new product development

Distributed and localised manufacturing

The term 'Distributed Manufacturing' (DM) refers to a conglomerate of distributed and autonomous production units which operate as a set of cooperating entities. The unique attributes of food products, such as perishability and stringent storage, make them considerably different to other manufactured goods, and particularly suitable for localised, distributed manufacturing.

The work has been to establish the feasibility of the application of DM to specific products in the food sector in order to reduce environmental impact and support local economies. The need for such a shift towards smaller scale local manufacturing has been highlighted by a range of factors such as changes in transport and labour costs, the availability and access to materials, energy and water and the need for long-term resilience to market changes.

The work has included:

- Feasibility Assessment of DM
- A range of specific characteristics and attributes associated with a food product will be used within a specially designed decision support model to assess the applicability of DM to a particular food sector.
- Detail Modelling of Distributed Manufacturing
- A simulation based approach will be used to provide a what-if scenario analysis capability to assess and evaluate the 'Key environmental and economical
- Performance Indicators (Ke2PIs)', associated with DM.
- Distributed Planning and Management
- A set of guidelines and algorithms will be developed to aid with future planning of distributed and localised food manufacturing.

DM presents the potential to increase manufacturing systems sustainability but needs to be carefully assessed in different scenarios to identify beneficial applications. Four alternative models for future

DM food production have been identified, and the **developed decision support methodology** through the creation of a two-step AHP (Analytical Hierarchy Process), and will facilitate the correct implementation and utilisation of DLM for future food production.

Additionally, and in collaboration with researchers across the CIM a report was commissioned by the 'Food, Energy and Water Local Nexus Network' (LNN), and aims to provide an overview of food technologies that could support the wider adoption and application of Re-Distributed Manufacturing (RDM) in the food sector:

https://www.centreforsmart.co.uk/publications/innovative-manufacturing-technologies-for-redistributed-manufacturing

One of the main findings of this study has been that RDM, as an innovative production structure, necessitates further research, innovation and development (RID) in order to enable successful applications by food businesses. These RID activities could be categorised under three areas of process level, product level and system level innovations. In this context, a number of key research questions regarding future development of food technologies for small scale production systems are presented. Based on these, the report also presents a number of specific research challenges that need to be addressed in order to develop a viable and sustainable approach to the production of food products on smaller scales (redistributed) and closer to the source of consumption (localised), whilst preserving the safety and maintaining the quality of manufactured food.

Finally, one of the main conclusions of this study is that increasing productivity, improving resilience and reducing waste are important considerations upon which the future of the UK food sector must be founded, and distributed manufacturing of our food products will play a vital role in the achievement of these goals.

Framework for enhancing resilience

Faced by a host of challenges, from Climate Change, to resource constraints, the UK's food supply chains, which are heavily dependent on supermarket logistics, are increasingly vulnerable to disruption.

This work explored what it means for actors at each step in our supply chains to be food resilient in the 21st century, developing a novel food and drink manufacturer specific **framework**, and begins by describing the process of identifying the scope and boundaries of the resilience sought. It then describes a real-time mapping process to identify a manufacturer's bespoke underlying vulnerabilities. Finally it details the process of identifying and evaluating specific countering resilience capabilities to each identified vulnerability so as to mitigate them in the most efficient way. Contrary to popular belief, resilience does not simply concern resisting a disruption. Rather, it is the ability to adequately anticipate potential disruptions, to react in such a way that disruption to standard operations is minimised and to learn and adapt in response to the disturbance, even if this requires fundamental changes to operational models. Understanding resilience in this way should allow much more refined matching of a given stakeholder's management options (known as capabilities) to the specific vulnerabilities facing them. However, there is a real need for further empirical research across the food supply chain (i.e. ranging from primary production to retail) to identify specific food sector capabilities and vulnerabilities, and the linkages and interactions between them.

There are currently few practical resilience tools implementable at a workplace level. In response, this research has developed a **workbook** which provides the reference charts and guidance for a food and drink manufacturer to enhance their resilience. The workbook has been validated via empirical case studies with two major chilled convenience food manufacturers in the UK. A major strength is the incorporation of bespoke user data to target response rather than relying on hypothetical or historic scenarios. Findings suggest that in volatile operating environments, resilience should not be seen as a one-off solution but rather as a cumulative series of constant adaptations to an ever evolving operating environment.

Utilisation of 'Internet of Things' to Improve Food Resource Efficiency

The Internet of Things (IoT) is capable of supporting numerous tasks in real-time such as tracking, locating, monitoring, measuring, analysing, planning and managing, and enhancing efficiency and transparency within food supply chains. This highlights the significant potential offered through the latest IoT advancements to support innovative approaches based on an automated real-time systems for monitoring and analysing the resource usage across entire food production and supply. Such timely management and provision of appropriate knowledge and information could potentially result in more effective strategic planning and better decision making in support of resource efficient and sustainable food supply chains.

This work has aimed to take advantage of recent advances in information technology to improve food supply chain (FSC) decisions through utilisation and application of the concepts and principles proposed by the 'Internet of Things (IoT)' to reduce resource consumption and other negative environmental impacts. A specially designed **'health check'** method and associated tools have been used to analyse and assess the environmental sustainability of a food supply chain. Enabled by a bespoke IoT based model collection, collation and monitoring of real-time data related to specific environmental impact will provide FSC decisions. An initial focus has been on developing a **food waste tracking system**, and results shows that detailed measurement of resources can lead to sustainable and resource-efficient food supply chain. Work has been carried out with Pukka Pies and Samworth Brothers to test some of the methodologies.

Sustainable new product development

The research builds upon the understanding of the use of environmental assessment tools and methodologies in the new product development process, and provide environmental performance decision support in the early product design and development phase to improve the long-term sustainability of the food sector.

The research investigated the benefits and challenges involved in adoption of a novel innovative approach to food product development. This included a wide range of considerations, for example, intelligent food packaging design that helps to increase the shelf-life of a fresh product and minimises postproduction waste, use of alternative protein sources for nutritionally optimised foods, and product reformulation based on seasonal and locally available ingredients.

This research has utilised the product development process as a tool to overcome the main obstacles in Food Sustainability through early intervention in the development decisions within a product life. Flexible new product development models will then be developed which are adaptable to the specific requirements of a specific product range. These NPD models explore additional information and knowledge required to reduce environmental impact throughout product life cycle.

Future plans

Utilisation of the IoT approach should come under three different lenses: Production; Supply Chain and Consumer Engagement. Links to the Digital Economy NetworkPlus, run out of the University of Lincoln, and opportunities are being sought.

Additionally, future and emerging business models are being assessed which will have impact on the food manufacturing industry, through challenges to supply chains and manufacture itself, as a results of changing consumer engagement with the purchasing and preparation of food.

4. Training and skills development

A key impact of the Centre has been its training and development of thought leaders of the future. Over its lifetime, the CIM has attracted a wide range of postgraduate and postdoctoral scholars to work as part of the team. The Centre has provided a plethora of development opportunities, including technical training, support in developing research skills and methodologies, and multiple occasions to interact with our broad network of members both nationally and internationally at conferences, workshops and industry events. Researchers were encouraged to take the lead in assessing the needs for their own development, and sessions were arranged and delivered to the cohort in Intellectual Property management, Project management and Working and collaborating in a CIM (delivered by EPSRC CIM in Regenerative Medicine). A team building event at the Seasoned Cooking School at Catton Hall, Derby (2015) focussed on ideation and had a talk on the funding landscape from KTN, and all researchers formed working groups in the future gazing exercise in the lead up to the Future Manufacturing Research Hub vision and submission. Working with the Outreach officer researchers were given the responsibility for organising and delivering the events at **Food Matter Live**. Researchers regularly met to discuss cross-research theme opportunities, with two notable interactions being work leading to a joint publication between Loughborough and Nottingham on waste valorisation, and the delivery of the Distributed Manufacturing report.

At all Universities researchers undertook personal development planning, as part of their bi-annual reviews, which has led to individual career planning, and in most cases progression into jobs within industry or academia. At Birmingham, doctoral and post-doctoral researchers had access to a wide range of activities organised by the Formulation Engineering CDT.

The Centre has therefore become a platform to support the future leaders of the sector. We are extremely proud the impact that each member has made and of the impact they continue to have as they progress through their careers.

The following profiles showcase how our researchers have developed their skills and research profiles as a result of their collaboration with the CIM.

Dr Joanne Gould: After completion of my PhD I was employed as a Research Fellow in the Centre until September 2017. My involvement with the CIM included attendance and oral presentations at the first three annual conferences, Food Matters Live, researcher cohort meetings, advisory boards and the mid-term review. During the three year post, I completed two research secondments with two of the CIM's industrial partners. I continued to investigate natural Pickering particles but was also encouraged to start developing my own area of research - Sustainable Proteins - starting with a focus on insect proteins. Research carried out during my time in the CIM was presented at international conferences such as Food Structure, Digestion and Health (New Zealand, 2015), Congress on Particle Technology (Germany, 2016), IUFOST World Congress (Ireland, 2016) and Insecta (Germany, 2017) and published in two peer reviewed journals. On Day 1 of postdoctoral life being given the autonomy to work within the themes of upgrading ingredients and food manufacture for healthy diets was daunting and after a relatively outlined studentship it felt like I had fallen off a cliff. However, the freedom to explore research ideas and publish these gave me the skills, confidence and eventually an actual research area for the next step of my career. The Centre's core of Birmingham, Loughborough and Nottingham alongside the Industrial partners introduced and gave me skills to deal with a completely different side of research forming ideas across universities, engaging in collaborations to writing grant applications. These and additional opportunities such as organising events, writing research summaries, justifying projects, secondments, industrial collaboration meetings, project management training, dissemination and outreach of the Centre's work were countless, challenging, often completely out of my comfort zone and at times they felt never-ending, but I could not have asked for a better foundation to an academic position. **I was appointed as an Assistant Professor in**

Food Science at the University of Nottingham in September 2017. My teaching responsibilities encompass protein and meat science to Undergraduates and Master Students as well as supervising research into the functionality of sustainable proteins in food microstructure design. Since being appointed, I have secured funding from the Industrial Challenge Strategy Fund for a PhD studentship investigating thermomechanical extrusion of future food materials and from the University for an MRes studentship studying the manufacture and consumer acceptance of insect protein gels.

Dr Patrick Webb: I joined the EPSRC Centre for Innovative Manufacturing (CIM) in Food as a Research Associate. My project during the CIM has focused on water use efficiency in food manufacturing. Water supply quality and reliability, and restrictions on effluent discharge contents and quantity, are already concerns for manufacturing industry in the UK and will become increasingly important. One of the things I enjoy most about my job is talking to industrial collaborators, understanding their problems and point of view, and going into factories and seeing the ingenious technical and operational solutions that have been implemented. The food industry is new to me because my previous experience has been in other areas of manufacturing, and I have appreciated the opportunity to learn about specific industry concerns with hygiene, short shelf life and rapidly changing demand. I have also seen many food industry concerns common with my previous experience, such as traceability and quality assurance. I have been able to bring to this research a combination of commercial and academic experience in innovation. My time at the Manufacturing Technology Centre gave me an insight that I value into many issues affecting academic –industrial relationships, such as differing time scales, drivers and reward mechanisms, and which I have tried to apply to my work for the CIM. I believe that these differing drivers can be negotiated successfully, that relationships of mutual respect can be constructed, and that these are mutually beneficial. For me the Centre for Innovative Manufacturing in Food provides an excellent example of how this can be done and I have been able to continue my association with the Centre in my role as **Lecturer at the University of Loughborough**.

Dr Ourania Gouseti: I was an associate member of the CIM through my post-doctoral work on crystal networks. This was conducted under the supervision of Prof Ian Norton at the University of Birmingham from June 2016 until February 2017. I have since been appointed Assistant Professor in Food Process Engineering, a career progression fully supported by the CIM.

As an associate member of the CIM I had the opportunity to become part of a wide network comprising of established and early career individuals with interests in innovative manufacturing in foods. This enabled me to familiarise myself with aspects of food manufacturing outside my core research topics and thus to gain a broad understanding of the field. It further enabled me to get involved in discussions related to the future and trends of food production with experts in the area, which influenced my own research interests. The project I was involved in at the CIM further enabled me to build links with the funding company. On an individual level, members of the CIM fully supported my career progression. I am fortunate to have been working as an **Assistant Professor in Food Process Engineering**, Faculty of Engineering, University of Nottingham since the end of my involvement in the CIM. I have enjoyed full support from CIM members in my first academic steps, including Prof Tim Foster, Dr Bettina Wolf, Dr David Gray, and Prof Ian Norton. Overall, I am grateful that I have been included in the CIM activities and I'm also grateful for the support I enjoyed as an associate CIM member and beyond.

Dr Leila Sheldrick: I worked to help set up the context for a number of the projects in the early stages of research development at Loughborough by writing job descriptions for postdoctoral researchers and PhD students which combined my personal research interests in user engagement in design of personalised foods and new networks of localised production. The CIM exposed me to new people, and new radical ways of interdisciplinary working. Through the events and collaborations established I have learned how to successfully spark new conversations and get people excited about working across disciplinary boundaries. I joined **Imperial College London** to help build and grow the new **Dyson School of Design Engineering which was established in 2015**. We are working on developing a brand new undergraduate programme and I have been working on the next stage of growth for our postgraduate programme, Global Innovation Design, run in partnership with the Royal College of Art. In addition, I have been establishing new research connections and focuses including envisioning future scenarios, developing new approaches for incorporating sustainability into product development processes, and harnessing ubiquitous computing and interactive technologies in design engineering.

Dr Antonio Sullo: In December 2013 (the first appointment!), I joined the CIM and continued my work on food microstructure in relation to fat crystallization in emulsion based chocolate and filled protein particles at the University of Birmingham in the group of Prof Ian Norton. At that time the research activity had just started and I contributed to the writing of a project proposal in drying and rehydration of food microstructures in relation to one of the CIM Grand Challenge (New Processing technology). During my year at the Centre I followed the initial stages of the project from presenting the research idea to the other partners of the Centre to the recruitment of PhD candidates and their guidance where appropriate. My experience at the CIM has been without doubt central to the role I have today in DIAGEO. The CIM provided a scientific network where to explore opportunities for collaborative research as well as exchange project ideas with R&D professional and experts from academia and industry. This diverse environment of technical experts helped me not only to progress my own research but also to develop skills beyond science. I learned to leverage external experts, to focus more on research impact, to link fundamental research to meaningful technology and to convey complex scientific information in an accessible way. All of the above skills have been extremely valuable for transitioning from academia to industry and overall for my career so far. Since the CIM I have been working at **DIAGEO Global R&D Centre** where I lead projects in the area of Food Colloids for iconic brands such as Baileys and Smirnoff. My role combines technical expertise with business knowledge to identify areas of high technical potential for the company. What makes my job scientifically challenging is the presence of ethanol in our products which adds an extra level of complexity to my research. Together with managing projects, I provide technical support to colleagues in other functions or other markets to solve complex, business-related problems with high commercial impact.

Dr Yadira Gonzalez-Espinosa: I joined the CIM in Food in 2015 after having completed an industrial research project on protein based Fluid gels as fat replacements for salad dressings for Kraft Foods, USA at the University of Birmingham.

My involvement in the Centre allowed me to continue growing in my career and further foster my passion for Food research. It gave me the opportunity to participate closely in the research, design and development of engineering strategies for tackling problems faced by the food industry. In particular, my research project looked at developing food microstructures assembled from main food building blocks (e.g. proteins and polysaccharides) which could give wide multi-functionality when included in more complexes food systems such as emulsions and be applied in several food applications especially targeting the delivery of bioactive compounds.

I think one of the main contributions that the centre has made to my career has been the building up of a wide network of contacts. Not only among my colleagues at the University of Birmingham but also with the other Universities involved in the centre. This has always allowed the constant sharing of ideas and expertise in different areas that help to move the research projects forwards. Such collaboration, for example, resulted in the publication of the article “Encapsulation systems for the delivery of hydrophilic nutraceuticals: Food application” published in the Journal of Biotechnology Advances. The annual meeting and other events organised by the centre served me enormously to establish connections with members of the food industry and other global Universities.

Overall, I think the experience, knowledge and skills I acquired working for the CIM helped me considerably in the progression of my career and in getting my current job as a **Research Fellow at the School of Food Science and Nutrition at the University of Leeds**. I continue working on the generation of microstructures not only for food but also for biomedical applications with the use of more sustainable and novel materials of current interest (e.g. chitosan) where our main aim is to test their applicability *In vivo* and performance in closely real food systems.

Working for the Centre has been very fulfilling personally and career wise. In particular, working with Professor Ian Norton, from whom I learnt a lot, has been very enlightening and a truly valuable experience. He gave me the opportunity to be involved in other activities that fostered my career such as the coordination and delivery of a Module addressed to undergraduate and MSc students “Food Microstructure and the consumers” as well as allowing me to lead of the Organisation of the 2nd UK Hydrocolloids Symposium, 2015 and co-supervise MSc and PhD students, all of which, have been professionally very rewarding.

Dr Aris Lazidis: Aris was a research fellow at the University of Birmingham. He holds an Engineering Doctorate from the same department, an MSc in Food Technology from Wageningen University (The Netherlands) and a BSc in Food Technology from the Technological Institute of Thessaloniki (Greece). During his career, he has worked on research projects closely with several food companies including Kerry, Mars, Cargill and Nestle. Aris has a number of research interests including:

- Designing interfaces (emulsions and foams) using surface actives materials (proteins and surfactants) and/or particulate structures (solid particles, microgels and crystals).
- Utilising hydrocolloids, fats and waxes in creating microstructures as structural elements of food with healthier nutritional profile compared to conventional ones.
- Developing low energy methods to create emulsions.
- Investigating the properties of new structures created in respect to the way they are processed in the mouth and to compare them with well-established foods for indulgence.
- Examine the effect of air bubbles on the sensorial properties of simple water and oil continuous food matrixes both in vitro and in vivo.

Aris also explored waxes as materials to create particles with an enhanced ability to adsorb and stabilise interfaces. Waxes, materials present in several natural foods that have been overlooked so far, poses the hydrophobicity necessary to adsorb on different interfaces (oil/water, air/water and air/oil). Work has been done to create spherical particles out of waxes that have shown exceptional foaming properties. Moreover, waxes have been utilised in creating a viscoelastic crystal network within oils which not only provides structure to liquid oils, that pose a healthy triglyceride profile, but also allows the incorporation and stabilisation of gas bubbles that can further reduce the calorific density of foods. Aris has published a review paper in Food Hydrocolloids entitled *‘Microstructural design of aerated food systems by soft solid materials’*. He currently has another manuscript under review. Aris is also part of the editorial team for the *Handbook of Food Structure Development* book which will be published by the Royal Society of Chemistry.

During his time working in the Centre he had the opportunity to work together with some of the other members with a wide-range of skills on collaborative projects related to his research but also towards fulfilling some of the goals of the Centre in Road mapping its future. His involvement in the Centre’s cohort events and annual conferences has given him the chance to present his work on a wider audience and network with different people from within academia and industry. Aris is now a Researcher at the **Nestle's NPTC Confectionary, York**.

Dr Aditya Nayak: I was associated with the EPSRC Centre for Innovative manufacturing in Food during my Marie Skłodowska-Curie Fellowship which I carried out in the School of Chemical Engineering, University of Birmingham under the mentorship of Professor Ian Norton.

In my Marie Curie Fellowship project entitled "Ayurvedic Bioactive Compounds Stabilized Pickering Double Emulsions" I used the nanonization technology to engineer the particle characteristics, such as size, morphology and polymorphism, of ayurvedic bioactives to optimize their Pickering ability to stabilize colloidal suspensions like emulsions. Obtained results were very major milestones in the search for the edible Pickering particles to use in food matrices.

During this fellowship, I was also able to obtain a Universitas 21 Fellowship to visit the University of Connecticut, USA, to work on the downstream processing of nanoparticles. Further, my involvement in the CIM allowed me to enhance my complimentary professional skills like Project Management. It also allowed me to interact with various potential stakeholders of my research outputs and peers from many different research disciplines during events like Centre for Innovative Manufacturing in Food annual Conference at Nottingham (2016). This has enabled me to learn more about the challenges and needs of my research domain and how I can contribute to address those challenges by using my knowledge and expertise.

I was successful in publishing three research publications in reputed scientific journals including Biotechnology Advances and Food Chemistry. Currently, two further research publications are under consideration. I was also able to present my research findings at various conferences, e.g. the 8th IUFoST World Congress of Food Science and Technology, Ireland (2016), the 3rd Global Conference on Microwave Energy Application, Spain (2016), and the 7th International Colloids Conference, Spain (2017). Aditya is currently a Research fellow at **INRA French National Institute for Agricultural Research**.

Dr Abigail Norton-Welch: In September 2015, Abigail joined the EPSRC Centre of Innovative Manufacturing (CIM) in Food as a Research Fellow. Abigail achieved her PhD at the University of Birmingham, researching hydrocolloid structures and emulsion formation, focusing on their use in biomedical applications.

Part of her research continued from the work achieved during her PhD, however now with a food and drink focus. Her research investigates how changing the solvent quality, including using salts, sugars and alcohols, influences the structuring process. This has, in part, resulted in a patent application.

The research developed to investigating how temperature set hydrocolloids (such as carrageenans and gellan) could be structured at 30oC. Abigail developed a new method of forming hydrocolloid gum structures, which had the rheological behaviour of a hydrocolloid fluid gel, but without needing to process at high temperatures. These gum structures were then used to stabilise emulsions and double emulsions for significantly longer periods of time, compared with the corresponding formulations where the gums were not present. Her research resulted in a patent, which highlighted both the novel structures, and the low energy processing which was developed during this research.

Abigail also has a keen interest in mixed hydrocolloid gel systems and the influence on a secondary polymer on the gel properties. Abigail has researched the addition of a second polymer, such as maltodextrin, to gellan and kappa carrageenan fluid gels. Mixed gel systems have been shown to enhance some gel properties, and have allowed for hydrocolloid gels to benefit a greater number of applications.

Joining the CIM was an exciting venture for Abigail, as it meant both the continuation of developing innovative formulations and processes, while giving a fresh challenge by applying her previous knowledge into the food sector. The Centre has also allowed Abigail to interact with researchers and academics from the other institutes, as well as company connections, which has helped to broaden her research areas and ideas.

While working within the CIM, Abigail also co-supervises PhD and EngD students based at the University of Birmingham. Abigail has also developed two PhD proposals in collaboration with two companies, with both being successfully granted. Abigail has built good relationships with the company sponsors and aims to broaden her industrial collaborations during the remaining time of the CIM. Abigail is currently a **Research Fellow at University of Birmingham**.

Dr Valentina Prosapio: I worked within the EPRSRC Centre for Innovative Manufacture in Food (CIM) from June 2016 to May 2018. In these two years, my main project focused on "Drying and rehydration", investigating the effects of drying techniques on the food microstructure with the aim of improving the product shelf-life and its rehydration ability. I was also interested in identifying strategies to make the drying process more sustainable in terms of energy consumption and environmental impact.

In this context, my research demonstrated that the application of osmotic dehydration as a pre-treatment prior to oven-drying and freeze-drying allows: the processing time to decrease, the rehydration ability of the dried products to improve and their colour and textural properties to be better preserved. A Life Cycle Assessment analysis (LCA), carried out in collaboration with the University of Salerno, also showed a reduction of the emissions of 25% for osmotic + freeze-drying compared to the traditional freeze-drying.

Over the last two years, I also co-supervised a PhD student who worked on drying and rehydration of gels. Our joint work focused on the study of the effects of different drying techniques (oven-drying, freeze-drying and supercritical CO_2 drying) on the gel microstructure. We observed that freeze-drying led to the attainment of a porous and uniform structure with higher rehydration ability. In addition, it was demonstrated that it is possible to modulate the mechanical properties of gellan gum gels by adjusting the pH of the solution during gelation and by acid/basic environment exposition. The research findings resulted in 6 papers, published in journals with high impact factor, which allowed me to improve my track record.

During the time spent working within the CIM, I had the opportunity to network with different groups across the centre and be involved in collaborative projects. CIM members brought expertise from different fields and the discussions about the future of the food industry contributed to my growth as a research fellow. CIM meetings and conferences allowed me to share the outcomes of my research, not only with academics from other universities, but also with industrial delegates who offered a different perspective to my project regarding the industrial needs and targets. Valentina is currently a **Research Fellow at University of Birmingham**.

Vincenzo di Bari: Dr Vincenzo di Bari is now a **Research Fellow at the University of Nottingham working on the Formulation for 3D printing: Creating a plug and play platform for a disruptive UK industry**. He attained his PhD at the School of Chemical Engineering at the University of Birmingham in December 2015. Prior to his PhD he graduated from Italy with a BSc Hons and MSc in Food Science and Technology at the Faculty of Agriculture in Foggia, Italy.

As a member of the CIM in Food, my research has developed mainly around one of the six Research Themes identified as 'Upgrading of Materials', which aims at the recovery and valorisation of natural biomaterials as well as transformation of waste streams for food applications. Specifically the two main research topics I am focused on are: (1) the use of oleogels: a novel route for the replacements of saturated and trans-unsaturated fats to structure edible oils in foods; (2) aqueous recovery of natural lipid organelles i.e. 'oleosomes' or 'oil bodies', from oil rich seeds for food emulsions applications.

The oleogels project started to address one of the Developed World key challenges: the reduction of 'unhealthy' fats in food products. 'Rice bran wax' (RBW) was selected as 'oleogelator' as it is an abundant food grade waste product available worldwide. This project, developed together with Dr Bettina Wolf and Professor Tim Foster, started with studying the thermal and rheological

When looking for post-doctoral research opportunities, the prospect of joining the EPSRC Centre for Innovative Manufacturing (CIM) in Food was attractive for its dynamic structure, i.e. partnership between three Universities, and by the 'Food System' approach. This approach offered a unique opportunity to work on new research challenges, which were relevant from a fundamental science as well as from an applied point of view.

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The research project aiming at the 'upgrade of oleosomes' addresses the global challenge of utilising sustainable natural ingredients for food production. The concept of using oleosomes in foods was introduced at the University of Nottingham by Dr David Gray. Through our research we have gained a deep understanding of the role of processing conditions on the quality of the final extract. This has allowed us to develop a novel extraction method which can be tailored to produce oleosome extracts with the desired properties. Our work also benefits from secondments at a national (Rothamsted Research Institute, Greencore and Unilever) and international (University of Wageningen) partners.

Working at the EPSRC CIM in Food has offered me many unique opportunities to face interdisciplinary challenges. I have really appreciated being part of such a diverse group and it is a great experience.

Dr Natalie Chiu: Natalie joined the CIM as Outreach Officer in December 2015, having followed on from the excellent work in the same role by ***Dr Jennie Lord***. Bothe have been responsible for the outward face of the CIM, and have coordinated the industrial contacts, the conferences and workshops run by the CIM, the attendance at Food matters Live, along with the other numerous outreach activities. ***Jennie is now a school teacher at a senior school in Nottingham,*** and ***Natalie is an Open Innovation manager at Mondelez.***

Other destinations of researchers within the CIM include: Phil Sheppard (**PDRA and Research Development Manager for the Centre for SMART**); Lucia Azanedo is now a **Research Assistant at Griffith Foods**; George Skouteris is a **PDRA at Loughborough University**; Felix Shin has begun a **PGCE**, Aicha Jellil is a **Consumer Engagement and Product Engineer at JLR**, Michelle Neville is a **Product Scientist for Unilever**, Suzanne Davies a **Product Technologist at PepsiCo**, María Natalia Mena Garzais a **Production Team Leader at Mondelēz International**, Filippo Bramante has started a **DTP linked to Rothamsted Research**, Ian Hamilton is a **Researcher at PepsiCo**, Steve Johnson is a **Technician in the UoN Food Process Engineering teaching programme**, Olayide Oladokun is a **Researcher with Carlsberg in Denmark,** Maria Benlloch-Tinoco is a **Lecturer at Northumbria University**, Robin Leaper is a **Researcher for the Channel 4 programme 'Food Unwrapped'**, and Rhianna Briars is a **Proposal Writer** for the **Technology Research Centre** near Newark.

PhD students in the process of completing their studies include Panagiotis Arkoumanis, Fabio Smaniotto, Motolani Sobanwa, Gladness-Marry Manecka, John Noon, Yi Ren, Elle warner, Farah Bader, Kurnia Ramadhan, Konstantinos Tsiamas, Izzi Tengku, Ernesto Tripodi, Saniye Samanci, James Huscroft, Holly Cuthill, Jade Phillips, Rania Harastani and Chris Clarke.

4. Achievements against goals and Future plans

The table below is the list of metrics we gave ourselves at the beginning of the project. As can be seen the large majority of the targets have been achieved or over achieved, with only the aggressive number of patents being only half achieved (to date). This is probably due to the fundamental nature of work conducted, and would have been addressed in the Future Manufacturing Research Hub, where a call for co-creation and a requirement of spanning Discovery; Understanding; Integration and Adaptation; Demonstration and Deployment. The section below outlines the publications that have come from researchers and academics associated with the CIM. There have also been countless presentations at International conferences, with keynotes delivered by academic members of staff, and ECR and PhDs finding valuable opportunity to spread the word of their research and impact of the CIM. Indeed two things of note should be recorded – the first a request to attend and present at SOCHITAL (the Chilean Society for Science and Technology) on Impactful Innovations and the role that the core funding plays, and more importantly the award of RSC's Food Group Junior Medal (2018) to Dr Joanne Gould.

One of the aspects that is most pleasing is the diversity we have achieved across almost all job families working in the CIM. We had involvement from 17 different nationalities, and in total a gender split of 54% male and 46% female (Academic – 65:35; Researcher – 39:61; Admin – 20:80; and Technical - 50:50).

Impact	Activity	Progress
Industry	Provide innovations to our industry members and provide trickle-down opportunities to SMEs (through engagement with SME member organisations and outreach activities)	Active engagement through workshops. Hosted the Food Innovation Network's national meeting at the third CIM conference. Have interacted with the D2N2 'Enabling Innovation project'.
	File 20 patent applications over the 5 years of the grant	10 patents emerging from the work to date.

	Organise at least one knowledge transfer workshop per Theme in the 5 years of the grant	5 knowledge transfer workshops organized, and contributions to D2N2 enabling innovation workshops. 2 co-creation workshops organized to set the scene for the research agenda of the future (taken up in **Food Sector R&D Need & Alignment with the 2017 Government Industrial Strategy**).
Policy	Continue to be members of Foodbest, ETP Food for Life, the UK NTP, CIRP and promote the multi-disciplinarity of the Centre	Contributions, through engagement with KTN Food Sector Strategy group to the KTN White paper 'Redesigning the food supply chain: choosing and producing healthy, nutritious and sustainable food', and the article mentioned above.
	Produce an Innovation Roadmap for the subsequent 5 years, showing income streams and technology areas to be mined through in-depth engagement with industry drivers	As above – the roadmap was developed, and continues to evolve.
Academia	Build on the integration of the 3 universities by identifying opportunities through the interaction with the MTC and aiming for 20% of our studentships to be cross-institutionally co-supervised.	Engagement with the MTC in the early stages of the CIM, and involved them in the co-creation workshops.
	Publish 90 papers in the 5 years of the grant in high ranking peer-reviewed academic journals	140 peer-review publications, 7 book chapters and 13 conference proceedings.
	Write a book covering the interdisciplinary nature of the work in the Centre by the end of the grant	RSC Publishing 'Development of Food Structure via Sustainable Processing Systems' eds. Spyropoulos, Lazidis and Norton in press.
	Organise 1 international conference in the 5 years of the grant	3 international conferences organized (2016, 2017 & 2018).
Human Capital	Through developments within the Centre's activities look for markers of success e.g. promotions, provision of tenure, new contracts for members of staff within the centre	2 promotions to Professor, 3 researchers given permanent academic tenure. 2 Administrator roles converted to full contracts and 1 Technical role with follow-on funding direct from Industry.
	Train PDRAs and PhDs so that they acquire employment in their chosen fields as they finish their research, and look to secure good	Identified in the body of the text, with high success rating for those who have completed their study.

	members of teams through new successful research proposals	
	Be the employer of choice by bringing in incoming and/or returning Marie Curie fellowships	Aditya Nayak was an incoming Marie Curie fellow, who now is a researcher in INRA, France. Guillermo Garcia-Garcia is applying for the returning Marie Curie fellowship.

<u>Future plans</u>

With the rejection of the Future Manufacturing Research hub bid, the identified directions may have to be taken up in smaller entities, losing the opportunity for National connectivity. However, this will be kept alive by continued participation in the KTN Food Sector Strategy group, and also increasing interaction with the Food Sector Council, through the FDF and Defra, and involvement in the role out of wave 2 of the food sector deal. Discussions within the Midlands Engine are also ongoing, where an area of Healthy Food manufacturing has identified both manufacturing and consumer behaviour drivers for scientific development. The changing landscape of consumer purchase engagement with food will continue to evolve, and the need for engineering and supply chain solutions to meet the needs of the future will continue to be sought.

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Patents:

The University of Birmingham

“Pickering emulsion formulations”
GB1407934.7 filed 06/05/2014 (Provisional priority application) PCT/GB2015/051333 filed 06/05/2015; EP1572995.5 filed 06/12/2016; US15/308,909 filed 06/11/2016

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GB1608595.3 filed 16/05/2016 (Provisional priority application); PCT/GB2017/051343 filed 15/05/2017

“Alcoholic compositions”
GB1710662.6 filed 03/07/2017 (Provisional priority application)

“Chocolate”
GB1707330.5 filed 07/04/2017 (Provisional priority application); PCT/GB2018/050939 filed 09/04/2018

In addition to the two patent families identified above there were two patents filed by companies sponsoring research in Prof Norton’s group:

“Food & beverage additive” (filed by Mondelez)
PCT/IB2013/000893 filed 09/04/2013 (Provisional priority application)

“Process for production of stable emulsions” (filed by Cargill)
EP13001653.8 filed 29/03/2013 (Provisional priority application); PCT/US2014/032140 filed 28/03/2014; EP2014748319 filed 29/10/2015; CA2908302 filed 29/09/2015; US14/781.113 filed 29/09/2015

The University of Nottingham

"Satiety gel"
GB2532697 (A) 25/05/2016; GB20160004686

3 patents under discussion.

Researchers, academics and industrialists enjoying the 3rd and 4th CIM International Conference in March 2017 (top) and March 2018 (bottom).