Institution: University of Edinburgh

Unit of Assessment: UoA 9 – Physics

Title of case study: From fundamental physics to formulation: the Edinburgh Complex Fluids Partnership supports innovation and commercial productivity

Period when the underpinning research was undertaken: 2002–2011

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Wilson C.K Poon	Professor	1990–present
Mark D. Haw	Research Fellow	1999–2005
Khoa N. Pham	Research Assistant	2003–2005
Peter N. Pusey	Professor	1991–2008
Alexander Morozov	Professor	2007–present
Cait MacPhee	Professor	2006–present
Vernita Gordon	Research Fellow	2003–2006

Period when the claimed impact occurred: August 2013–December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Attribution: The Edinburgh Complex Fluids Partnership (ECFP) was founded in 2012 to provide a vibrant environment for knowledge exchange between the Soft Matter and Biological Physics group at the University of Edinburgh (UoE) and industry.

Impact: ECFP has helped generate at least GBP8,300,000 of value for companies through improving process efficiency, supporting R&D, new product development, waste reduction, and providing evidence for claims of product efficacy that have led to further investments.

Beneficiaries: Small and medium-sized enterprises (SMEs) and multinational companies. Employees of these companies who have also benefitted from training in fundamental soft matter physics principles and techniques.

Significance and Reach: Since August 2013, ECFP has completed 100 projects with 49 companies across 12 sectors, 45% of which were UK-based SMEs. ECFP's support for SMEs, which account for >99% of private sector businesses in the UK, is particularly important: these companies typically have few internal resources for understanding and exploiting the science underpinning their formulated products.

2. Underpinning research

The Edinburgh Complex Fluids Partnership acts as a conduit for knowledge exchange between UoE's Soft Matter and Biological Physics group and industry. Soft matter (colloids, polymers and surfactant aggregates) forms the backbone of a range of industries. 'Real life' examples include paint, sun-cream, perfume, printer-ink, weed-killer and ice cream. Product formulation and optimisation of manufacturing processes have historically relied on empirical methods due to a lack of understanding of how component parts interact to produce observed bulk behaviour. The UoE Soft Matter group uses model systems to investigate how physical interactions determine bulk behaviour in a variety of soft materials.

A longstanding strength of the UoE group is in the study of colloids, especially the formation of microstructure through phase separation and kinetic arrest due to physical interactions, and the resulting effect on the bulk properties of a material such as flow behaviour and stability. For example:

- A study of the evaporation of colloid-polymer mixtures [***R1***] demonstrates that **gelation qualitatively changes the drying behaviour of droplets**, giving physical insights for predicting final coating properties in inks and agrochemicals. A detailed study of the flow properties of a **model colloid-polymer system** revealed a two-step yielding process for an attraction-dominated system and linked macroscopic properties to microscopic interactions [***R2***].

- The **rheology of multicomponent fluids** determines fluid behaviour during use. Turbulence in solutions reduces the efficiency of manufacturing processes and can be initiated or reduced by the presence of polymers [***R3***]. Theoretical perspectives and computer simulation enable experimentalists to interpret rheological measurements and understand how **polymer conformation** changes during flow.
- Other fundamental work has examined how pH-mediated electrostatic interactions affect the **structure and stability of protein aggregates** [***R4***].
- A key distinction between colloids and polymers is the importance of the **elongational viscosity** in the latter, which can give rise to unique behaviours [***R5***].
- Lipids are membrane-forming bio-surfactants. A series of **confocal microscopy** papers, e.g. [***R6***], have demonstrated how the **composition of mixed lipid membranes forming unilamellar vesicles controls the formation of surface domain structures**, with implications for biophysical properties such as adhesion.

Underlying this programme of research is the group's commitment to bidirectional knowledge exchange: injecting basic science to industry, but also drawing inspiration for new basic research from its encounter with industrial practice.

3. References to the research

[***R1***] **M. D. Haw,** M. Gillie and **W. Poon**, *Effects of phase behaviour on the drying of colloidal suspensions,* Langmuir, 18, 5, p1626-1633 (2002)
DOI: https://doi.org/10.1021/la0110951 *[69 citations, WoK]*

[***R2***] **K. N. Pham,** G. Petekedis, D. Vlassopoylos, S. U. Egelhaaf, **W. C. K. Poon and P. N. Pusey**, *Yielding behaviour of repulsion- and attraction- dominated colloidal glasses*, Journal of Rheology, 52(2), 649, (2008) DOI: https://doi.org/10.1122/1.2838255 *[194 citations, WoK]*

[***R3***] E. Sultan, J. –W. V. de Meent, E. Somfai, **A. Morozov**, and W. van Saarloos, *Polymer rheology simulations at the meso- and macroscopic scale*, Europhysics Letters. 90, 6, p. - 6 p., 64002 (2010) DOI: https://doi.org/10.1209/0295-5075/90/64002 *[7 citations, WoK]*

[***R4***] S. L. Shammas, T. P. J. Knowles, A. J. Baldwin, **C. E. MacPhee**, M. E. Welland, C. M. Dobson, G. L. Devlin, *Perturbation of the Stability of Amyloid Fibrils through Alteration of Electrostatic Interactions*, Biophys. J. 100 (2011) 2783-2791.
DOI: https://doi.org/10.1016/j.bpj.2011.04.039 *[76 citations, WoK]*

[***R5***] P. Becherer, **A. N. Morozov** and W. van Saarloos, *Scaling of singular structures in extensional flow of dilute polymer solutions*, J. Non-Newtonian Fluid Mech. 153 (2008) 183-190. DOI: https://doi.org/10.1016/j.jnnfm.2007.12.009 *[17 citations, WoK]*

[***R6***] **V. D. Gordon**, M. Deserno, C. M. J. Andrew, S. U. Egelhaaf and **W. C. K. Poon**, *Adhesion promotes phase separation in mixed-lipid membranes*, EPL (Europhys. Lett.) 84 (2008) 48003. DOI: https://doi.org/10.1209/0295-5075/84/48003 *[33 citations, WoK]*

4. Details of the impact

The Edinburgh Complex Fluids Partnership (ECFP) (www.edinburghcomplexfluids.com)

Between August 2013 and December 2020, ECFP carried out 100 projects with 49 companies operating in 12 different sectors (Figure 1) [***I1***]. Of these projects, 45% were with UK-based SMEs and the remainder were with multinationals.

To generate partnerships, ECFP has run biennial "Informulation" workshops since September 2013 [***I1b***]. These give academics and industrialists opportunities to discuss ideas and problems relating to their formulated products. Approximately 150 industry researchers have attended to date and 50% of 1:1 sessions held between industry and subject specialists in ECFP have led to a collaborative project. In addition to directly helping companies solve problems and innovate, these projects expose employees to ideas and advances in fundamental soft matter physics principles and techniques. Reciprocally, 16 postdoctoral and

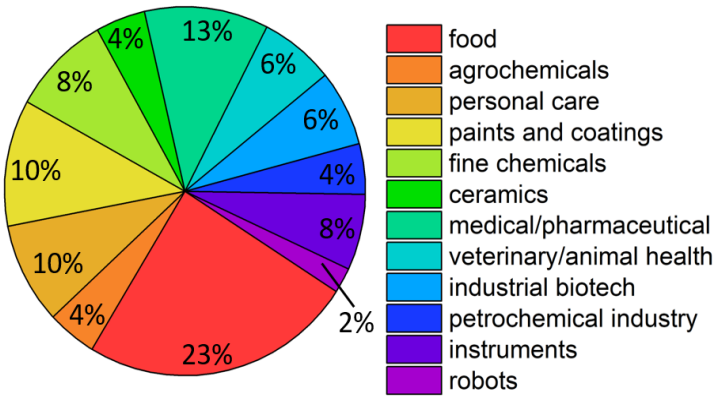

Figure 1: Pie chart showing the sector breakdown of the 49 companies ECFP worked with between August 2013 and December 2020.

academic scientists at UoE have gained experience in solving industrial challenges; 2 now work for commercial companies and 2 in research commercialisation roles. UoE students also benefit: 8 PhD students and 5 undergraduates have undertaken industrial placements. This impact is recogised by Skills Development Scotland, who have identified ECFP as a source of training that "*will transform current manufacturing processes and provide the knowledge … for a highly skilled workforce*" [***I2a***].

Transferring soft matter physics to industrial formulations

Below are representative examples of industrial impact generated by ECFP.

Optimising production processes: *Lamellar Biomedical Ltd* focusses on the commercial exploitation of natural lamellar bodies – fragments of stacks of multi-component lipid membranes – to deliver a variety of clinical benefits. ECFP used its expertise in multi-component lipid membranes [***R6***] to help the company optimise production and quality control protocols of their lamellar bodies. ECFP expertise in complex fluids rheology [***R2***] also provided the company with their first biophysical insight into how their lamellar bodies modified the viscosity of human mucus. The company states (in 2017) that *"being able to demonstrate an increased understanding of the mechanism of efficacy" … as well as our improved manufacturing control contributed to our success in generating an additional GBP5,750,000 in Series C venture capital investment funding"* [***I3***]. A Knowledge Transfer Partnership was subsequently established in 2018. Dr Simon Weir from ECFP characterised the flow of cystic fibrosis (CF) sputum and developed an artificial version of the material. The company state that as "*human CF sputum is a difficult material to work … ECFP's rheological expertise has been invaluable*". Weir also trained members of *Lamellar's* preclinical team in rheological methods to allow them to investigate CF sputum in their own laboratory [***I3***].

Glycomar markets high-value polysaccharides – a biopolymer – to the pharma, personal care and nutrition sectors. ECFP's complex fluid rheology expertise [***R2***, ***R3***] enabled a 2014 partnership with the company to evaluate and optimise handling and production conditions of a micro-algae-derived polysaccharide. This contributed to a 50% improvement in polysaccharide yield and led to the establishment of a new company (*Prasinotech*) to market the new product (Prasinoguard). Prasinoguard is targeted at the skincare industry, with a projected market value of EUR2,000,000 (02-2020) by 2021 [***I4***]. The rheological properties reported by ECFP are provided in marketing materials for prospective customers as evidence of the formulation possibilities offered by the product [***I4***]. The project also trained *Glycomar* staff in the interpretation of rheological data [***I4***].

Reducing waste: *Mentholatum* requested characterisation work in 2014 to examine the rheological properties of three pain-relief products: Deep Heat, Deep Relief, and Deep Freeze. The company were completing a GBP10,000,000 upgrade of their manufacturing plant and wanted to ensure the new, larger scale had not altered products' microstructure. Analysis carried out by ECFP using rheology [***R2***, ***R3***], confocal microscopy [***R6***] and other techniques revealed a discrepancy and prevented waste production [text removed for publication] [***I5***]. The upgraded factory has doubled *Mentholatum's* production capacity to 3,000kg batches and the company cites ECFP's work [***I5***] as helping it meet the commercially sensitive deadline for the plant's validation. This ensured they could continue supplying these products to 20,000,000 customers in Europe, the Middle East, and Africa.

A separate project in 2018 used ECFP's expertise in the drying of soft matter [***R1***] and in image analysis [***R6***] to help demonstrate the acceptability of the microstructure of a new ibuprofen gel under development [text removed for publication] [***I5***].

Product development: *Reacta Biotech* is a start-up developing edible formulations for the clinical diagnosis of food allergens. To prevent patients being aware of allergen dosage, it is essential that test samples and placebos achieve a similar mouth feel. The company worked with ECFP in 2015, drawing on the group's rheology expertise [***R2***], to show that this was indeed the case. The rheological analysis from ECFP's final report was included in the company's subsequent patent application to support their claim of indistinguishable mouth feel [***I6a***]. This patent has strengthened the company's intellectual property position and they raised new investment of GBP1,250,000 in April 2020 [***I6b***].

New testing procedures: *Marlow Foods* produce the meat substitute Quorn. The company's ongoing expansion into the vegan market has required reformulation of recipes containing egg white. In a 2016 project, ECFP used the group's expertise in electrostatic effects in proteins [***R4***] to reveal how salts within mycoprotein-based gels affected their texture. The company drew from ECFP's final report to design a novel testing protocol now used within the development workflow for new vegan products [***I7***]. This range is commercially valuable to the company (*"in the UK, sales have grown from nothing in 2015 to a significant sub brand, now available in every major supermarket chain in the UK and beyond*") [***I7***].

Supporting R&D: *Croda Europe Ltd*. make high-performance ingredients for multiple sectors, including agrochemicals, where coating uniformity is a major concern, especially if the formulations contain particulates. In 2016, using the group's expertise in drying of colloidal suspensions [***R1***], ECFP developed a technique to characterise the structure of colloid-polymer coatings after drops have dried. This method is now used by 20 employees working in research laboratories in the UK, India, Brazil, and the USA. *Croda* states that it allows the company to "*differentiate ourselves from our competitors and improve recommendations to customers. Internally, this method is used to characterise the effects of exciting and new development products"* [***I8***].

Fujifilm's Imaging Colorants division manufactures pigment dispersions for use within ink formulations. ECFP collaborated with the division in 2015, utilising the group's expertise in the depletion attraction within colloidal systems [***R1***]. Prior to this partnership, dispersions displaying instability (e.g. sedimentation or aggregation of pigment particles) were adjusted empirically without understanding the root cause. The company report that ECFP "*provided us with knowledge and in-house capability to test pigment dispersions and determine which mechanism promotes aggregation for each type of pigment-polymer mixture ... enabling us to optimise the concentration of polymer to provide an acceptable shelf-life for our customers*" [***I9***]. During the REF period, the development and launch of 4 new products have benefitted from this work [text removed for publication]. An additional 7 products currently under development apply knowledge derived from the partnership: the improved understanding of stability mechanisms "*focuses troubleshooting and allows us to address sedimentation problems in a systematic manner*" [***I9***].

Bringing new products to market: *Pawsitively Natural* benefitted from ECFP's expertise in drying colloidal mixture [***R1***] and protein aggregation [***R4***] during a project to adjust the formulation of novel dog biscuits to reduce breakage. The company began trading with this new product in January 2014 [***I10a***] and the CEO said "*what underpinned everything that I did to develop the products was in the work … with Dr Tiffany Wood [ECFP] … literally building the products up from a scientific perspective. It's worked marvellously, I've seen sales increase, particularly since I won Interface Innovation of the Year award*" [***I10b***].

Savings generated via understanding product behaviour: *Hyaltech,* a subsidiary of Zeiss, manufactures viscoelastic fluids used in cataract eye surgery. [text removed for publication] The company is now able to "*provide a much more detailed rationale for product specifications*" [text removed for publication]. Additionally, the collaboration improved the company's understanding of solution behaviour during manufacturing [text removed for publication] [***I11***].

Expanding the UK's formulation capabilities: *The National Formulation Centre (NFC)* was established by government as a part of the Centre for Process Innovation (CPI) to improve the interfacing between academia and the formulation industry. In 2017, ECFP used the group's expertise in formulating and studying well-defined model systems [***R1***] to partner with Leeds and Birmingham in an NFC project to develop an open-access, benchtop-to-pilot-scale testing facility [***I12***]. ECFP developed simple model formulations to characterise the instrumentation designed for novel formulation scale-up. This is an essential part of commercialisation but many companies, especially SMEs, do not have the resources to build their own test plants. The new infrastructure fills this need, providing a platform to scale-up formulations in a data-driven manner and take them from the lab to market. CPI's Chief Technology and Innovation Officer commented that the facility "*will ensure the UK's formulated products manufacturing sector remains at the vanguard of innovation."* [***I12***].

Informing industry strategy: ECFP advocates for the importance of soft matter physics research within formulation science [***R6***]. Chemical Sciences Scotland recognised ECFP as a key partner for industry in their Strategic Plan for 2025, where formulation was included for the first time as a focus area for improved manufacturing [***I2b***]. ECFP's co-founder, Dr Tiffany Wood, set up the Formulation Forum within the Society of Chemical Industry to enable industry to "*discuss their needs in a non-competitive environment with academia and other experts"* [***I13***]. Since 2018, the Forum has organised annual two-day workshops with attendance ranging from 90 to 130 delegates from industry and academia [***I13***]. It also contributed to the Chemistry Council's 2018 launch of its five-year strategy to the UK government's Department for Business, Energy, and Industrial Strategy [***I13***]. "Formulation for the Future" was recognised as a priority area [***I2c***]; research by ECFP scientists has been important in demonstrating how fundamental soft matter physics principles can be applied to optimise formulation design [***R1-6***].

5. Sources to corroborate the impact

[***I1***] ECFP's website
a) https://www.edinburghcomplexfluids.com/about-us
b) https://www.edinburghcomplexfluids.com/latest/events
[***I2***] Extracts from publicly available documents:
a) Skills development Scotland report: https://www.skillsdevelopmentscotland.co.uk/media/44645/life-and-chemical-sciences-sip-digital.pdf (page 14);
b) Chemical Sciences Scotland 2025 Strategic Plan (PDF document; pages 6 and 10);
c) Chemistry Council 2018 strategy https://ukchemistrygrowth.com/wp-content/uploads/2019/02/Chemistry-Council_v17_lr.pdf (pages 5, 17, 19, and 48)
[***I3***] Support letter from Lamellar Biomedical Chief Financial Officer
[***I4***] Support letter from GlycoMar Scientific Manager
[***I5***] Support letter from Mentholatum Director of Research & Quality Development
[***I6***] **a)** Patent citing ECFP project https://patents.google.com/patent/WO2018104691A1/en;
b) Investment information from Crunchbase: https://www.crunchbase.com/organization/reacta-biotech
[***I7***] Support letter from Marlow Foods Head of Research and Development
[***I8***] Support letter from Croda Europe Research & Technology Manager
[***I9***] Support letter from Fujifilm Research and Development New Product Development Manager
[***I10***] **a)** Guardian article: https://www.theguardian.com/small-business-network/2014/sep/04/showcase-marketing-pr-pawsitively-natural;
b) Video of CEO discussing the collaboration with ECFP (screenshots and a transcript provided)
[***I11***] Support letter from Hyaltech Ltd Managing Director
[***I12***] Press release from the CPI: https://hvm.catapult.org.uk/news/cpi-collaborates-on-cutting-edge-testing-facility-to-advance-formulated-liquid-manufacturing/
[***I13***] Support letter from Chair of the Formulation Forum