Institution: University of Greenwich

Unit of Assessment: 12 – Engineering

Title of case study: Transforming Quality and Efficiency in Handling of Particulate Materials in Industry: 'QPM' and related projects including the 'Powder Flowability Tester'

Period when the underpinning research was undertaken: January 2000 – December 2020

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:
Michael S. A. Bradley	Professor	01/10/1988 – present
Richard J. Farnish	Principal Research Fellow	15/01/1996 – present
Robert J. Berry	Research Fellow	01/04/2002 – 12/04/2020
Tong Deng	Post-doctoral researcher	26/07/2001 – present
Mark Cross	Professor	01/07/1982 – 31/12/2004
Alan R. Reed	Professor	01/12/1977 – 31/12/2017
Mayur K. Patel	Professor	01/05/1987 – present

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

Powder handling is important because almost all manufactured products incorporate particulate materials in their manufacture. Problems that cause poor quality, low throughput and extended time to market are extremely common. Research at the university's Wolfson Centre for Bulk Solids Handling Technology has resulted in a series of instruments, analysis techniques, software, training and spin-out research that has helped a large number of companies (e.g. BASF, Unilever, Drax Power, Roche Pharma, LG Chem Korea) reduce risk in new powder and bulk solids processes and troubleshoot existing ones. The case is typical of the influence that The Wolfson Centre has had on industry awareness and practice in the UK and globally. Highlights include embedment of research outputs in a £240M project that kept a £4Bn p.a. business open and saved 12M tonnes p.a. of CO_2, widespread use of research across businesses producing more than £1Bn worth of equipment p.a. and an instrument that is used in over 500 companies globally

2. Underpinning research

The Quality in Particulate-based Manufacturing (QPM) project (EPSRC GR/M15057/01).
From 1998 to 2002, the Wolfson Centre for Bulk Solids Handling Technology led three academic and six industry groups collaborating on this project which received government and industry funding exceeding GBP2,000,000. **Bradley** and **Cross** were the UoG investigators involved in this project that aimed to develop techniques to predict the level of 'quality loss' in handling of particulate materials through conveying, storage and logistics processes. The research was stimulated by the large financial losses from these causes experienced by many industries that involve powders, granules and grains as their feedstocks, intermediates and finished products. The output of that work was a 'toolkit' consisting of: • Techniques **[3.1-3.3]** including three novel instruments to measure the propensity of particulate materials to suffer from the three main problems identified, namely particle breakage (degradation), caking (lump formation) and segregation (demixing); • Process models enabling the instrument outputs to be used in conjunction with process conditions, to predict the degree of the problem to be expected in a new process, hence enabling new manufacturing processes and products to be analysed prior to finalisation of their design or formulation, and existing ones to be improved through 'what if' studies. Detailed study of many plants processing solids led to a deep insight into the common problems, their causes, and the properties of the particulate materials that control this behaviour.

Researchers at Wolfson Centre developed a novel powder flowability measuring device.
From 2004 to 2009 an instrument arising from QPM was the novel (manually operated) shear tester for measurement of powder strength. Originally conceived to measure the strength of caked powders, it became the basis of further research at the Wolfson Centre by one of the QPM investigators (**Bradley**, PI) and researchers (**Berry**). This DEFRA and international industry-funded project (AFM 206) on the **Powder Flowability Tester (PFT)**, delivered a fully robotised, automated instrument, which has widened the use of powder flow property measurement

throughout industry globally (over 500 companies). Poor or erratic powder flow causes great loss of productivity, so there was a clear need for an instrument usable by non-specialists to assess the handling problems inherent in any given powder, to: • assist with formulation (engineering the powder to avoid the problem); • design of the equipment around the powder to avoid or eliminate the difficulty, • quality control on powder products in production and purchasing.

The Wolfson Centre had a central role in the Virtual Formulation Laboratory (VFL) project. Since 2016, Wolfson has been a leading member of the EPSRC funded "*Virtual Formulation Laboratory*" project (EP/N025261/1) **[G1]** aimed at developing the underpinning research and integrating software to produce a user friendly tool to allow assessment of new or proposed particulate formulation blends in terms of their manufacturability at a very early stage, (before clinical or performance trials) allowing the potential for the said problems to be predicted and avoided by adjusting the formulation, or by selecting suitable manufacturing processes that are designed to control the issues, to avoid costly delays to market, reformulation or re-tooling **[3.7].**

Research outputs from these related projects underpinned eight more closely-related bulk solids research projects in Wolfson, with **Bradley**, **Berry**, **Deng** or **Farnish** as PIs. These include EPSRC (eg. GR/M15057/01, GR/S70937/01, EP/N025261/1, totaling > £1.35m), DEFRA (eg. AFM-206, AFT 167, AFM 276, totaling > £400k), British Coal Utilisation Research Association (eg. B66, B69, B89, just < £200k), EU (eg. FP6-MOBILITY 512247, £39k), and many funded by industry. These focused on diverse aspects of bulk solids processing including plant wear by bulk solids, powder formulation for favourable handling properties, optical sorting of particles, soil remediation, on-line measurement of flow properties, handling of wet ores, coal handling, pneumatic conveying **[3.5]**, fluidised powder transport, biomass handling, powder electrostatics **[3.6]**, powder metallurgy and others. The VFL project in particular has spawned various related research projects whose outputs are being integrated into it, key ones including a new method for characterising the surface energy of particles using milligram samples, in a way that can be used to predict the flow properties of the same substance in any particle size, and a new cellular-automata modelling tool to predict segregation, both of which are now being used by industry for process optimisation.

The result has been an extensive body of knowledge and expertise giving "wall-to-wall" coverage of issues involved in handling and dry processing of particulates, across many industries such as pharmaceuticals, food, metallurgy, mining, power, and waste that face the same problems of difficult flow behaviour and loss of quality (demixing, particle breakage and aggregation). The research addressed how these issues can be prevented through improving the design of the powder formulation or of the manufacturing plant, before expensive losses are incurred; or, where a problem already exists, finding a way to solve it, by improving either formulation or equipment.

3. References to the research

1. Chapelle, P., Christakis, N., Wang, J., Strusevich, N., **Patel, M. K.**, **Cross, M.**, Abou-Chakra, H., Baxter, J., & Tuzun, U. (2005). Application of simulation technologies in the analysis of granular material behaviour during transport and storage. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *219*(1), 43–52. http://dx.doi.org/10.1243/095440805X7044
2. Abou-Chakra, H., Tuzun, U., Bridle, I., Leaper, M., **Bradley, M. S. A.,** & **Reed, A. R.** (2003). An investigation of particle degradation by impact within a centrifugal accelerator type degradation tester. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *217*(3), 257–266. http://dx.doi.org/10.1243/095440803322328908
3. Christakis, N., Chapelle, P., Strusevitch, N., Bridle, I., Baxter, J., **Patel, M.**, Cross, M., Tüzün, U., **Reed, A. R.**, **Bradley, M. S. A**. (2006). A hybrid numerical model for predicting segregation during core flow discharge. *Advanced Powder Technology*, *17*(6), 641-662. http://dx.doi.org/10.1163/156855206778917715
4. **Berry, R. J.,** & **Bradley, M. S. A.** (2007). Investigation of the effect of test procedure factors on the failure loci and derived failure functions obtained from annular shear cells. *Powder technology*, *174*(1-2), 60–63. http://dx.doi.org/10.1016/j.powtec.2006.10.023

5. **Deng, T**., **Farnish, R. J**., & **Bradley, M**. (2008). Evaluation of particle degradation due to high-speed impacts in a pneumatic handling system. *Particulate Science and Technology, 26*(5), 438–450. http://dx.doi.org/10.1080/02726350802367522
6. Hussain, T., Kaialy, W., **Deng, T**., **Bradley, M. S. A.**, Nokhodchib, A., Armour-Chélu, D. (2013). A novel sensing technique for measurement of magnitude and polarity of electrostatic charge distribution across individual particles, *Int. J. Pharmaceutics, 441(1-2)*, 781–789 http://dx.doi.org/10.1016/j.ijpharm.2012.10.002
7. Salehi, Hamid, Berry, Robert, Farnish, Richard and Bradley, Mike (2019) A new uniaxial compression tester: development and application. Chemical Engineering Transactions, 74. pp. 463-468. ISSN 2283-9216 https://doi.org/10.3303/CET1974078

Indicators of research quality:
Accolades recognising the quality of the outputs and impact of the cited research:

- **QPM project:** IChemE Awards 2006 (Chemistry Innovation Award for Innovation in Applied Catalysis and Colloid Science): Highly Commended
- **Powder Flowability Tester (PFT):** R&D magazine top 100 (USA) 2011: R&D 100 Award
- **PFT:** IMechE Bulk Materials Handling Award for Innovation 2012 (certificate available)
- **PFT:** Runner-up in IChemE Innovation Awards 2010 (certificate available)
- **PFT:** Shortlisted in Times Higher Education Awards 2010 (certificate available)

G1 Grant: IC Sinka, **MSA Bradley**, *Virtual Formulation Laboratory* EPSRC (EP/N025261/1), Jan 2017 – May 2021, £1,741,953. **Per Section 2, multiple other grants furthered this work**.

4. Details of the impact

The research outputs have been developed into a number of "delivery vehicles" which have been adopted and embedded widely by industry:

- In-depth insight into the key issues with powder quality and flow on a large number of industrial plants that have been studied (approx. 30 during the research and 200 more since), which have been built into the dissemination routes described below. These include such issues as where to look for causes of problems in a plant; how to obtain meaningful samples from the plant and characterise them in ways that synthesise the behaviour seen on-plant; how to redesign equipment to avoid problems; and how to use the techniques to ensure right-first-time designs.
- A series of innovative instruments and facilities used by industry (the Brookfield Powder Flowability Tester; QPM Segregation and Degradation Testers, Caking Test Suite, Mechanical Surface Energy tester) for measuring behaviour of powders, specifically their flow properties and their tendencies to segregate, degrade and cake in handling, processing and storage.
- A series of techniques for using the results from the above-mentioned instruments – mainly analytical and numerical models, several of which are incorporated into the Virtual Formulation Laboratory software suite – to predict the behaviour of the powders in industrial processes (e.g. storage, transport, feeding/dispensing, heating/cooling, conveying) for use in plant design, powder formulation and process trouble-shooting.
- A much augmented series of paid educational courses for engineers in industry, to allow them to use this knowledge practically in their companies, attended by over 250 delegates annually.
- A consultancy service by The Wolfson Centre used extensively by industry (+50 projects worth around £550k annually) for design of new plants, development of new powder formulations and troubleshooting of existing ones, e.g. eliminating problems with poor flow, caking, degradation or segregation of particulates, fugitive dust etc. that are commonly costly in powder processing.

Since August 2013, more than 60 companies around the globe (from SMEs to multinationals) have funded over £3,000,000 worth of programmes of consultancy or applied research at Wolfson, to embed the outputs from the QPM and consequent projects. They either embedded the instruments and techniques directly in their own material characterisation and product design roadmaps, or funded studies at Wolfson to research the behaviour and formulation of their own materials further using the QPM, PFT and VFL techniques, and using the outputs of these projects in their plants.

Example 1: Decarbonising 5% of the UK's electricity: The world's largest biomass power project involved the conversion of 4 of the 6 units of the 3960MW Drax coal fired power station to biomass. Wolfson was engaged from the outset to deploy QPM techniques to optimise design of the new £240,000,000 fuel handling, storage and feeding facility **[5.1]**. (The gravity of solids handling to this conversion can be judged from the fact that the new fuel handling system cost £240M whereas changes to combustion systems cost only £70M). This involved predicting and minimising the physical degradation of the wood pellet fuel in handling (dust and fires compromise safety, performance and efficiency) and ensuring reliable flow. The research was applied in design of large and small storage silos for flow, structural stability, humidity and fire control; feeders and chutes for minimum fuel degradation and equipment wear; conveying systems for reliable fuel transfer; dust control; and fire and explosion protection. A close relationship has continued, Drax funding 12 further research and consultancy projects **[5.2]** to enable success in further improving their handling system, dealing with changes in the fuel, and eliminating snags. Benefits lie in helping preserve this £4Bn p.a. business and 5% of UK electricity supply, that would have closed without this conversion, and eliminating 12M tonnes p.a. of CO_2 from UK electricity production.
Similar design and support was provided to conversion of other large power stations: Lynemouth (2014-present); Tilbury (2010-2016), Eemshaven (NL) (2016 – present) and others. Since 2015, support has been provided to the burgeoning generation of smaller new-build biomass stations (e.g. Blackburn Meadows, Wilton, Irving etc.) **[5.8]**.
At the small end of the scale (domestic heat), a close relationship has been formed with UK Pellet Council. Wolfson prepares and delivers mandatory training courses for those involved with domestic pellet manufacture and delivery, embodying the research outputs.
Similar studies have also been made at the other end of the fuel supply chain via Enviva Corporation (major US manufacturers of biomass fuel for power stations worldwide), who have extensively paid for access to this body of research and techniques, to improve the quality of the fuel they deliver, reducing problems of self-heating, fire, dust explosions, handling problems etc.
Along the supply chain, ports e.g. Tyne, Immingham, Liverpool have accessed and used the research to reduce fires, environmental pollution, occupational dust exposure and cargo damage.
Example 2: The Brookfield PFT Powder Flow Testers (brookfieldengineering.com) arising from QPM via the following DEFRA AFM 206 research. Manufactured in the US by multinational Ametek-Brookfield and sold globally, around 500 machines (value ~£6,000,000) in 30+ countries since 2013 **[5.3, 5.9]**. Now the most widely used shear tester worldwide for measuring behaviour of powders, in industries as diverse as food, pharmaceuticals, energy, chemicals and any others that use powders. The use of these instruments helps safeguard quality of powder products worth many billions across these many companies and sectors. In addition to instruments in use in industry, since 2014, a further 60+ companies have embedded through over 100 funded projects of consultancy or applied research at Wolfson, based on use of the instrument and its underpinning research on powder flow, to research and improve their feedstocks, processes and products.
The research led to over 200 embedment projects funded by 150 companies since 2014. Powder processors including pharma, food, minerals, powder metallurgy and chemicals overseas and in the UK, including blue-chips such as ***GlaxoSmithKline*** (protecting £Bn's of production annually), ***Masterfoods***, ***Norgine*** **[5.4]**, ***Unilever, Roche Pharma*** **[5.5]** and many others. The impacts are improvements to the design of new or existing plants which process many billions of pounds of product annually, an enduring impact of on-going benefits to process efficiency and/or product quality in products ranging from cosmetics, drugs and snack foods to cement, automotive parts and power generation. The outputs are also disseminated through educational courses for engineers in industry (www.bulksolids.com), attended by nearly 700 paying delegates from over 200 companies since 2014, including delivery at 30+ companies in the UK, EU and overseas including India and China; demand is accelerating. Since early 2020, all these have been delivered on-line at a distance and numbers have increased to over 250 engineers per year.
Many companies in the UK solids handling equipment supply industry (+£1Bn p.a., 45% exported) used the techniques to improve their design practices, often experiencing large growth as a result of their improved service, e.g. SME ***Fairport Engineering*** **[5.6]** growing from £5M to £17M p.a. The large value of this impact across many companies is corroborated by the Solids Handling and Processing Association **[5.6]**, Materials Handling Engineers Association **[5.7]**, and IMechE **[5.9]**.

Nature of the creation of business value mostly centres around recognising, understanding and accommodating the unique behaviour of every individual powder, including:

- *Characterisation instruments:* Previously, few companies had means to measure flow behaviour of powders. Suppliers and users of powder processing equipment had only guesswork or experience to inform equipment designs, leading to frequent under-performance, financial loss, warranty claims, litigation and bankruptcies. The Brookfield PFT allows them to design or select equipment or powders correctly, reducing losses.
- *Equipment design:* Models from the research are used to predict and optimise the performance of proposed equipment designs ahead of building, greatly reducing problems.
- *Powder formulation:* previously, formulators of powders e.g. pharmaceutical oral solid dose preparations, snack flavourings etc. could not predict whether a new formulation would present manufacturing problems. Making and trialling a production-sized batch frequently led to major losses (~£200,000 for a failed batch of a pharmaceutical) and lost time to market. Using these research outputs, they can now predict approximately how their formulations will process even before first making them, making an accurate assessment from a few grammes, avoiding these costs and time setbacks by correcting formulation or equipment choice at the earliest stage of product development and production planning.
- *Educational courses* raise awareness of the difficulties in developing powders and plants for production of powder-containing products, convincing delegates of the need to characterise powders and use the models to realise business value. Frequently they feed back that they have, due to this awareness, recognised and avoided costly mistakes.
- *Forensic engineering* of failed processes, structural collapse of plants, badly-performing products etc. allow lessons to be learned and avoided in the future, preventing losses.
- *Safety of operators and plant* benefits by identifying and eliminating potential dangers; dust emission leading to inhalation and explosion, self-heating leading to fire, silo blockages that have to be dug out by hand, manual intervention to obtain flow of toxic materials etc.
- *Fast, affordable expert services* through Wolfson consultancy, on all the above and practical expertise to use them. Engineers, managers and formulators in industry can access these without having to become experts themselves. Many do evolve into company experts, and many such companies become sponsors and collaborators in research.

The integration of research, consultancy and education creates a virtuous circle; Increasing numbers of companies and individuals who access and use the techniques to improve profitability, creates a “good news” message stimulating further engagement and growth of powder processing research, not just at Wolfson but in academe world-wide through our many international links.

5. Sources to corroborate the impact

Testimonials:

1. Drax conversion project Technical Director: The use of the QPM, PFT etc characterisation and design techniques as central to the design of the world’s largest biomass power project.
2. Drax Power: Value of research impact in coal-biomass conversion and continuing since.
3. Ametek-Brookfield: The collaboration with Wolfson enabling delivery of the Powder Flowability Tester, and its reach into global industry, also IMechE Innovation Award Certificate.
4. Norgine Ltd: The advantages yielded to production and products from the research outputs
5. Roche Pharmaceuticals: The importance of QPM and VFL research in their developing new technology of continuous manufacture of drug products
6. Fairport Eng. Ltd: Increased business due in part to use of Wolfson research
7. Solids Handling and Processing Association: Embedment and impact of the QPM, PFT and VFL research and its spin-outs, on the £1Bn+ UK industry in this field
8. Materials Handling Engineers Association: Breadth of impact of Wolfson across the field
9. IMechE statement corroborating value of Wolfson Research in solids handling business