Institution: University of Bath

Unit of Assessment: 10: Mathematical Sciences

(a) Context

The UoA, coincident with the Dept of Mathematical Sciences at Bath, has a long tradition of applied research and engagement with industry, underpinned by a strong theoretical base. We have internationally renowned research groupings in *Algebra & Geometry, Analysis & Differential Equations, Continuum Mechanics, Dynamical Systems & Complexity, Industrial Applied Mathematics, Mathematical Biology, Mathematical Control Theory, Numerical Analysis, Probability* and *Statistics*. Our strength and coherence across a wide range of mathematical sciences makes us distinctive within the UK context, and indeed internationally. We embrace and enhance the unity of mathematics and its applications, as we believe that this is the way of the future for the discipline.

Our impact extends outside the traditional realm of the mathematical sciences and a significant part of our research tackles problems of importance to end users. In the past five years, we have worked with the agro-chemical industry, analysed problems of safety and decommissioning for the nuclear industry, developed methods for use in oil exploration, produced mathematical models for the financial industry, and advised water and power companies. Medical applications of our statistical research include clinical trials and surgery for cleft lip/palate. Improved computational methods for weather forecasting have benefitted both the Met Office and the commercial and public services that rely on their forecasts. We have contributed to the management of forests, the protection of fish stocks and provided mathematical models to study the spread of disease in bees. Our models for the effect of environmental pollutants on individuals have been used by the US Environmental Protection Agency to define new criteria for permitted levels, now enshrined in US government law.

The UoA hosted the following University Research Centres during the period 2008-2013. Bath Institute for Complex Systems (2002-2009); Centre for Mathematical Biology (est 1994); Centre for Networks and Collective Behaviour (est 2013); Centre for Nonlinear Mechanics (est 2003). Additionally, the UoA hosts Prob-L@B, the Probability Laboratory at Bath (est 2007), which has recently become a University Research Centre. These centres provide an outwardly visible research focus, extending contacts with external partners, and have played a key role in facilitating and enhancing the impact of our research.

We detail below how our research has produced impacts in the following areas: economy, environment, health, professional services, public engagement, public policy.

(b) Approach to impact during the period 2008-13

The UoA supported a number of activities designed to create impact. These, in a strengthened and enhanced form, will also form part of our impact strategy for the next five years, see (c) below.

Contact with end users. The UoA has a suite of long-term industrial research collaborations which we continually seek to expand. In some cases the end user engagement motivates new application-specific research, while in others the ubiquity of the underlying mathematical problem has led to core mathematical research with broad potential for applications. Even with tightly focused research questions, treating problems in mathematical generality can lead to solutions with a much broader reach, e.g., moving mesh methods for numerical solution of partial differential equations (PDEs), or general theory and computational methods for group sequential clinical trials.

Interdisciplinary seminars and working groups. Budd organised workshops in Bath with participants from industry, including workshops on *Delamination and Folding* and *Industrial Complexity*; Jennison has cultivated relationships with the pharma industry through talks at conferences aimed at research users (PSI, SMi, ADAPT, BfARM/DIA, East User Group), short courses at conferences (IBC, BASS, ADAPT, PharmIQ, VIB, Deming), seminars and training courses at companies (GSK, Roche, AstraZeneca, Merck Serono, Pfizer, Takeda), and web-based presentations (KOL and ACRP webinars); short courses to audiences including end users were also given by Lindgren (9 courses, e.g. RSS Avon Group, 2013) and Wood (10 courses, e.g. Joint Statistical Meeting, 2012).

Student placements. Through our long-running very successful UG industrial training scheme (12 months) and our industrial MSc projects (including a 6-month placement option), we have some 60 pre-existing contacts with government and private industry: indeed, many students have subsequently found employment via this route. A number of research collaborations have arisen from interactions with industrial partners via associated placement visits (e.g. two CASE awards with Pfizer and one with Roche). Industrialists attend the Industrial Advisory Board for the MSc annually in Bath and this has fostered much research activity e.g., adaptive numerical methods for fuel tank modelling (Airbus), noise pollution from wind turbines (Hoare Lea), and mathematical models for microwave oven cooking (CCFRA Technology).

Several PhD projects have been directly supported by industry: Graham has supervised two CASE awards with AMEC on reactor safety and one with Schlumberger on seismic inversion, Jennison has supervised two CASE awards with Pfizer on clinical trial design and supervised a PhD student on clinical trial design fully supported by AstraZeneca, Sweden. We plan to introduce short term industrial placements as part of a new PhD program in Statistical Applied Mathematics.

International forums for knowledge transfer. Participation is encouraged and supported, recent highlights include:

The annual UK and European Study Groups with Industry provide natural fora for our staff and PhD students to meet potential research users from outside academia, and are regularly attended by strong cohorts from Bath. Budd is on the scientific board for the Smith Institute which coordinates study groups.

Participation in SIAM and ICIAM meetings: for example, Dawes co-chaired Applications of Dynamical Systems in 2011, Budd gave a highlighted outreach talk at ICIAM 2011.

From July-Dec 2011, Scheichl (Chair), Graham and Freitag organised a prestigious Special Semester at the Radon Institute of the Austrian Academy of Science, entitled *Multiscale Simulation with Applications in Energy and the Environment,* with strong senior industrial involvement.

Research projects. Many of the UoA's research projects have benefitted from industrial support and engagement, and this has naturally led to impact. Funded projects include: Scheichl, EPSRC grant for risk assessment of waste disposal sites with the Nuclear Decommissioning Authority and AMEC; Budd and Zimmer, EU FIRST project with Siemens on interface tracking methods for PDEs; Scheichl, NERC grant with Met Office; Graham, EPSRC grant on high frequency waves with Schlumberger, Met Office, BAE Systems and Institute of Cancer Research; Jennison, EU IMI project DIRECT on diabetes with 24 partners, including four pharma companies; Zimmer, collaboration with Nippon Steel on grain size distribution which led to a successful EU Marie Curie postdoc application.

Research projects with end users have beeen scientifically successful, leading to economic and societal impact. While the best examples are contained in REF3b, there are many other examples, e.g., Scheichl with the Met Office (new solvers for PDEs on spherical geometries) and Graham with AMEC (robust reactor safety computation).

Other research projects have been motivated by applications without the initial involvement of specific partners, for example Wood's work on efficient methods for fitting generalized additive models and Lindgren's work on Bayesian computation for spatial modelling have both subsequently found applications in end user contexts (e.g., EDF and WHO**,** respectively).

Consultancies. Consultancies on implementation of research findings and methodologies have often led to new research with impact. Examples include: Faraway, consultancy with 3D medical imaging company 3DMD (USA) and with BASF (Germany); Jennison, consultancy with the pharmaceutical companies Merck Serono, Takeda, EISAI; Scheichl, subcontracts with Lawrence Livermore Lab; Shaddick, consultancy to Wessex Water and contracts with Western Power Distribution. With the aid of EPSRC KTA and KTN (Smith Institute) funding, we have transferred research findings to industry by embedding researchers with the Met Office and with Thales UK.

Disseminating research to end user audiences. Members of the UoA frequently present their research at fora involving industry, e.g., Jennison in the "Open for Business" day at the INI workshop on Design of Experiments in Healthcare, and short courses by Lindgren and Wood.

A number of our publications include "case study" or "tutorial" material aimed at promoting impact. For example, Logemann and Ryan's 36 page front cover featured tutorial article in *IEEE Control Systems* (Aug 2011), the largest circulation technical periodical worldwide, describes recent

research developments in absolute stability theory (including their own work). Recipients of the magazine include around 9000 industrial engineers who are members of the IEEE Control Systems Society.

Members of the Probability group regularly give presentations attended by employees of finance companies, for example, the 2010 "Crossing Barriers" conference at Bath was attended by Morgan Stanley's Head of Global Market Modelling.

To assist with technology transfer, we have published open source software (Wood's mgcv package in *R*, Shaddick's pCNEM software) or provided computer code to research partners as deliverables in funded projects (Scheichl, AMEC). In other cases, our work has been implemented by others (Jennison's group sequential methods in the free *R* package gsDesign and in the commercial software *East*).

Public Engagement. The UoA has a long tradition of public engagement, including holding Royal Institution Masterclasses for local schools, coaching the UK Mathematics Olympiad team, offering a public engagement project module to UGs, and running the award-winning annual Science Fair *Bath Taps into Science* (since 2000).

Types of impact stemming from our research

Economic impacts. More accurate weather forecasts improve the commercial and public services provided by the Met Office (Budd and Scheichl). Numerical methods for the control of nuclear power stations are commercially crucial for AMEC and have strong environmental and public safety implications (Graham). Spatio-temporal analysis of tree and soil data has guided management of a vast forestry resource (Augustin). Improved clinical trial methodology has benefitted companies developing new drugs (Jennison).

Impacts on public policy and service. Shaddick's models for personal exposure to pollutants were applied by the US Environmental Protection Agency in work that underpinned new legislation in 2012; his consultancy with the World Health Organisation has informed their policy decisions.

Health impacts. Faraway's statistical modelling of facial motion is used by surgeons in operations for cleft lip/palate. By accelerating the drug development process, improved clinical trial design brings earlier benefits to a wide patient population (Jennison).

Impacts on practitioners and professional services. Wood's statistical models as implemented in the mgcv package are used for setting quotas for fish catches. Medical statisticians in industry and the public sector use methods developed by Jennison and associated software.

Impacts on the environment. Our case studies offer clear examples in forestry management (Augustin), fishery policy (Wood), and control of air pollutants (Shaddick). In an application of mathematical biology, Britton has worked with the British Beekeepers Association on a project funded by the Food and Environmental Research Agency to investigate and control the spread of disease in bees by Varroa mites.

Impacts arising from public engagement. Explaining mathematical research to a general audience is challenging, but the UoA achieved this at the Royal Society's 350th Anniversary Summer Exhibition in July 2010, where Budd, Dawes, Freitag, E Spence and Zimmer presented the exhibit *Living in a Complex World*, seen by around 50,000 members of the public. Exhibits were selected partly on their links to current research.

Support from the Department that enables staff to achieve impact. Established contacts with a wide range of industrial partners facilitate the building of impact for new and established members of the UoA. Our mentoring of junior staff encourages them to work alongside senior colleagues when engaging with external partners (for example Freitag worked with Budd on Data Assimilation with the Met Office). Our policies on sabbatical leave, the staff workload model, and academic staff promotion all explicitly recognise the value of KT, encouraging follow-on activities to generate impact and public engagement. Staff are rewarded for undertaking consultancy, through salary or through the creation of a research fund for the staff member's use.

In the more applied areas, the strength of collaborations with end users has been a factor in staff appointments and promotions. The vitality engendered by this type of research is recognised by the Department and the University.

Institutional expertise and facilities drawn on by the Department. Central university structures are orientated towards maximising the impact of research projects (e.g. through the award of targeted university studentships and advice on Pathways to Impact). The University Research

Committee initiates and promotes institutional support for all research and impact related activities. Administrative support is coordinated by the Research Development and Support Office (RDSO) which maintains the internal *Impact Gateway* webpage and its *Research Development & Collaborations* team advises on the development of links with external research users and consultancy agreements.

The University has a thriving portfolio of KT funding, including an EPSRC KT Account (£3.5M over the period 2009-2012), an EPSRC Impact Acceleration Account (£1.4M over the period 2012-2015) and a HEFCE HEIF allocation (£2.4M over the period 2011-2015). These funds support internal competitive schemes for delivering external engagement. The UoA has successfully bid to all these schemes and to the Smith Institute's KTN fund in order to enhance the range of our impact. We have appointed a 'KT Champion' (Dawes) who has actively engaged with the KT agenda across the University and the KT Forum, developing KT-related support to enable an agile response from the UoA. University services including Staff Development, the Public Engagement Unit, and the University Library play a full part in supporting our impact agenda.

(c) Strategy and plans for supporting impact

In the period 2008-13, the UoA's impact related activities have been guided by the strategic principles 1-6 below. These principles will be continued and enhanced in the next five years.

1. Appointment of members of staff with cross-disciplinary focus.
2. Recognition of impact-related activities in workload model and cases for promotion.
3. Exploitation of UG and MSc industrial training programmes for new research collaborations.
4. Taking advantage of the University's EPSRC Impact Acceleration Grants (IAG).
5. Financial support for participation by staff in forums for KT, research sandpits, interdisciplinary seminars and working groups involving external partners.
6. Active participation by staff in UK and EU collaborative grants with end users, and in consultancies, initiated through our industrial training partners and other contacts.

Moreover, in the next five years, the following additional strategies will play a key role.

7. Application to the University for the formation of an interdisciplinary Research Institute, led by the UoA, to collaborate with other disciplines which use mathematical sciences in a crucial way. The recently announced University of Bath institute initiative is a vehicle for supporting and developing impact.
8. Development of an innovative PhD industrial internship scheme.
9. Extension of the role of the KT Champion to include external KT relevant opportunities, to coordinate and monitor impact related activities and to initiate new impact specific projects.

In addition, a central strategy for the next five years will be to bring our research in applied mathematics into closer contact with probability and statistics, supporting engagement with end users whose problems have a complex, multi-scale character where models for small-scale processes may be stochastic, but on larger scales, deterministic models are more appropriate. The coupling of the stochastic and the deterministic is a rich source of potential impact and several recent new projects, e.g. Kyprianou with Scheichl and Shardlow with Lindgren (funded by IAG) will be vigorously continued. The recently established University Research Centre for Networks and Collective Behaviour (led by Mathematical Sciences) and the appointments of ECRs Rogers and Stauffer will further support our development at the deterministic-stochastic interface.

(d) The relationships between the unit's approach to impact and the submitted case studies

The five case studies demonstrate the success of our approach to impact described above. The impact achieved is based on long-term relationships of members of staff with external parties, which have been nurtured through consultancies and student participation in both academic and industrial aspects of the research over a number of years. In some instances, the underlying research was conducted without direct involvement of the end user, in others, underlying research results were obtained in close collaboration with end users. In all cases, the research was informed by detailed knowledge and experience of relevant application contexts acquired through long-term relationships.