Institution: University of Sheffield

Unit of Assessment: 10 - Mathematical Sciences

a. Context

SoMaS has a longstanding tradition of impact in both engineering applications of fluid dynamics and applied statistics. This has been given new impetus by the increasing emphasis on impact by government, expressed through research council funding procedures, and as part of the research strategy of the University of Sheffield. Developments within SoMaS have also led to a widening of the areas with economic and societal impact, with examples across the range of mathematics and statistics. A further trend has been towards multi-disciplinary and collaborative research; this frequently involves mathematicians and statisticians serving in team projects with significant impact, as exemplified by the four Impact Case Studies. Areas of collaborative work involving departments in Sheffield and elsewhere include archaeology (planning), biology (food security, gene sequencing), climate science (ecology, geography, engineering & industry), engineering (industry), geography (planning, policy making) and medicine.

Applied statistics has a long history in SoMaS, but recent activity has focused on industrial applications of Bayesian statistics through the RCUK funded Modelling Uncertainty in Complex Systems (MUCM) project led by **O'Hagan** and **Oakley**, a new EPSRC funded project with the Advanced Manufacturing Research Centre (**Oakley** and **Stillman**) and statistical archaeology (**Blackwell** and **Buck**). All have contributed to our case studies. Statistical methodology developed in the School is also translated into impact through the Sheffield Statistical Services Unit (SSU), which is a commercial statistical consultancy within the School.

Two aspects of engineering mathematics that have contributed to the case studies are work by **Rees** on natural gas storage and **Quegan** on climate science. Our number theory group is linked to GCHQ through the Heilbronn Institute.

b. Approach to impact

Our view is that the most interesting and powerful impacts from the mathematical sciences grow from deep knowledge, appreciation of its significance, and an eagerness to see it exploited. Accordingly, we take our balanced range of expertise as the starting point: all areas have potential for impact, but some are closer to realizing the potential than others. An imaginative and proactive attitude to impact is perhaps more important in achieving impact than the area of study, and this attitude is a criterion during staff recruitment.

We have an Impact Champion within the School, who offers advice and support to individual members of staff on the achievement of REF Impact, and who acts as an advocate to ensure efforts to achieve impact are supported and rewarded. Both the Impact Champion and Director of Research oversee the impact lifecycle of research in the School.

The University supports impact through its Research and Innovations Services (RIS) unit, whose knowledge transfer team helps us to value, identify and develop commercial opportunities; it also works closely with our partners, supported by >£5m investment from HEIF and our EPSRC Knowledge Exchange Account, to maximise the impact of our research on economic and societal benefit. The School has hosted drop-in sessions with relevant staff from RIS, and staff are encouraged to attend meetings organised by the University's three Knowledge Transfer Networks, where they can network with representatives from industry and the wider community. Similarly, we have benefited from Open Days at the Advanced Manufacturing Research Centre and the University's newly created Manufacturing Forum. Our Fluid Mechanics group participates actively in the university-wide Sheffield Fluid Mechanics Group, which has proven to be an excellent route to industrial applications of fluid mechanics. In addition, the Sheffield Science Gateway provides a team of specialists in building business partnerships between researchers in the University's Faculty of Science and key players in industry, global corporations, smaller enterprises, professional bodies and Government agencies.

The University has very flexible mechanisms for rewarding staff through promotion and Exceptional Contribution Awards and these take impact into consideration. In particular, SoMaS

includes impact considerations when making recommendations to Faculty on such rewards. In addition, contributions that facilitate Impact count towards workload allocations.

The key to Impact is the development of relations with external bodies and this is often a long process. We recognise this and reflect it in our staff development strategy. For example, **Quegan** has been supported over many years with a reduced teaching load in order to develop a multi-disciplinary multi-institution environmental research centre, one of whose fruits is the recent commitment by the European space Agency to launch the BIOMASS satellite with funding of €370M. Providing such support has also allowed him to develop his international reputation in environmental observation that led to him accompanying the Brazil trip by the Government Chief Scientist Sir John Beddington, to attend the Brazil-UK Climate Collaboration conference in 2011.

Rees's involvement in the development of a novel rheometer to carry out a full rheological characterisation of complex fluids in real time is attracting considerable interest from industry and illustrates several elements of our approach to impact. We have made outward visits, such as when 2 PDRAs and 1 PhD student visited Kraft at Bourneville. We have hosted visits from Advanced Microwave Technologies, Molecular Control Systems and a company that makes floor coverings. We have had tele-conferences with Glaxo and Unilever and regular email contact with several other companies. Most of these links were made following articles in the press or trade journals. The Kraft collaboration is supported by a collaborative EPSRC Knowledge Transfer Account to the University of Sheffield. As here, we encourage shared CASE PhD students or PDRAs, wherever possible.

To help maximise impact from the recently completed Modelling Uncertainty in Complex Systems project, SoMaS is funding a part-time administrator for one year to help set up an international network (The MUCM community) to take MUCM methods to users. The Statistical Services Unit, with its long-standing relationships with external companies such as Astra Zeneca and Glaxo, provides a good conduit for other applied statistics projects. Other statistics areas contributing to impact include face recognition (**Fieller**), which has attracted funding from the FBI, and gene regulatory networks (**Juarez**).

The relationship with GCHQ followed full-year secondments in the last RAE assessment period and is maintained through the Heilbronn Institute by extended visits by our staff (**Jarvis** and **Snaith**), attendance at Heilbronn conferences, and supporting Heilbronn academics to give seminars and interact with Sheffield staff.

c. Strategy and plans

The long route to Impact is overseen by the Impact Champion, who, with the Director of Research, identifies projects with particular potential for impact and ensures that they have adequate support and, with the help of the University Research and Innovations Service, that researchers are guided through the impact process. Annual Impact Away days are used to highlight current projects leading towards Impact, to share experience and to identify new opportunities for Impact. The Impact Champion also manages a tracking and reporting system for projects with potential for Impact over their full lifetime, so that appropriate evidence can be collected shared and archived

As part of the process of grant application, there is an internal review during which the Pathways to Impact are scrutinised. In particular, reviewers ensure that Impact is properly considered in proposals within the criteria set out by the Research Councils, and that adequate resources to support impact are requested. This early assessment of potential Impact is critically important in ensuring that appropriate support mechanisms are put in place.

Once projects show real prospects of Impact, the Impact Champion and Research Committee keep oversight of their progress. Staff can apply to Research Committee for funds for pump priming activities to support Impact (for example this led to **Rees** obtaining a knowledge transfer award of £10K on a project involving Glaxo). Advice is available from the Universities Research and Innovation Services Knowledge Transfer team, with promotion through the Science Gateway. The workload allocation model gives proper weight to Impact work, allowing staff time to pursue it as the project develops. Study Leave can be used in pursuit of Impact, and acceleration of Study

Leave can be permitted where this is critical for Impact. Once Impact is fully established, supporting documentation is gathered and archived. The Science Gateway then provides specialist capabilities in its promotion, taking due account of confidentiality and intellectual property issues.

Impact is linked to staffing strategy since an active interest in generating impact is one of the factors used in selecting new staff. Several areas that have been effective in generating impact in the past (applied statistics, fluid mechanics and number theory) are under continuing development, as they also have excellent prospects for the future. The creation of the Mathematical Biology group opens up a wide new range of potential impact directions, and the use of topological methods to recognize patterns in large data sets and to provide measures of biodiversity give further prospects.

d. Relationship to case studies

We describe here the background for each case study, indicating how the research of each contributor has developed into impact beyond academia.

1) *Natural Gas Storage (**Rees**).* The mathematics component of the liquid natural gas storage project formed part of a collaborative study between SoMaS and the Dept. of Chemical and Biological Engineering (CBE). CBE have a long-standing collaboration with the company MHT Ltd, which is based in Richmond in North Yorkshire. They have co-funded 2 industrial KTP associates, who spent extended periods at Richmond. **Rees** has interacted with these associates at meetings of the COMSOL study group, which is held weekly during term-time, and to which researchers from across the University who use this Multiphysics Finite Element Software package are encouraged to attend.

2) *Uncertainty in Computer Models (**Oakley***). For the past six years, research on uncertainty in computer model predictions has been organised through the RCUK Managing Uncertainty in Complex Models project led by **Oakley** and **O'Hagan**. To develop relationship with key users/beneficiaries, the project has an Advisory Panel with members from both academia and industry. This included representatives from the Food and Environment Research Agency, the Hadley Centre, Rolls Royce and GlaxoSmithKline. Advisory Panel members were invited to two two-day meetings every year, where they could interact with researchers and help shape the research agenda.

3) *BIOMASS (**Quegan**).*The key activity was to propose the BIOMASS mission and lead the science team in an 8-year intensely competitive pan-European process to select the next European Space Agency (ESA) Earth Explorer mission. This led to the selection of BIOMASS in May 2013, for launch in 2020, at a cost of €370M, most of which will go into European industry. It will have many other financial spin-offs, not least because of the huge budgets associated with carbon trading and funding to developing countries for better management of their forest resources.

4) *Radiocarbon Calibration Curves (**Blackwell**, **Buck**, **Heaton**)*. **Buck**'s involvement with statistical archaeology began with her PhD where she helped develop tools that enable archaeologists to calibrate groups of related radiocarbon determinations. This framework is now known as Bayesian radiocarbon calibration and is implemented in freely available software, including BCal (bcal.shef.ac.uk). In 2001 **Buck** was the first statistician to be invited to join the international working group which collates data for and provides internationally agreed estimates of the radiocarbon calibration curves. She quickly realised that the data structures were considerably more complex than had previously been articulated and that the various data sources exhibited high levels of correlation which had also previously been ignored. This led her to develop, with **Blackwell** and a series of PDRAs, a fully probabilistic approach to curve estimation, together with new theory and methods, on which all the estimates of the internationally-agreed calibration curves have been based since 2004. **Buck** regularly attends meetings and workshops with academic, public sector and commercial users of the calibration curves and with those who supply the data from which they are estimated. Through this network of connections, the Sheffield team are well placed to develop new methods as they are needed and to help users to make best use of new curve estimates as they are released.