Institution: University of Liverpool

Unit of Assessment: 10 Mathematical Sciences

a. Context

Research interests in the Department span the whole spectrum of mathematical sciences, with a corresponding variety of paths to impact. A unifying theme is that practical applications of our research are facilitated by our active network of multidisciplinary links. Our research clusters, Applied Mathematics (**AM**), Statistics and Probability (**SP**), Financial and Actuarial Mathematics (**FAM**), Pure Mathematics (**PM**), and Theoretical Physics (**TP**), achieve impact in a variety of ways. In **AM**, for example, research in mathematical biology has been used by DEFRA and the Veterinary Laboratories Agencies leading to policy impacts on disease control procedures. Other work in this area includes research at the Centre for Mathematical Imaging Techniques (CMIT), which specialises in novel numerical techniques for analysing imaging data and applies its expertise primarily to medical imaging in collaboration with the NHS. Research in wave motion has had an economic and societal impact on industrial design for bridges and nuclear reactors. In **SP**, research in statistics is used by government agencies such as the NHS, leading to health and policy impacts such as changes in NHS guidelines. In the new **FAM** cluster, research is leading to economic impact on the practices of insurance companies. Research in **PM** has contributed to economic and cultural change through the application of singularity theory to computer vision (with applications to sculpture and online retail described in a Case Study). All departmental research activities inform our strong tradition of public engagement and outreach, especially in schools; the fundamental research in **TP** having a particular resonance with the public.

b. Approach to impact

Policies and Processes: The University has a Pro-Vice-Chancellor for Research and Knowledge Exchange (KE), as well as a KE Strategy Group, which is attended by a KE lead from the School of Physical Sciences and further supported by a Research and KE Manager in the Faculty of Science and Engineering. As part of a STFC-funded Innovations Partnership Scheme (IPS), the School recently appointed a fellow to co-ordinate KE strategy within Nuclear Physics, Particle Physics and Accelerator Science. Regular meetings of all research cluster leaders throughout the School facilitate joint approaches to problems of interest. A Deputy Head of Department (DHoD) has executive responsibility for promoting Impact, KE and Outreach. The DHoD is supported by a KE committee that formulates the Department's strategy and oversees its implementation. Each research cluster within the Department is tasked with formulating a plan to identify, develop and foster impact from its research, and it is now standard practice to question candidates for an academic position or for promotion on their attitudes and ideas concerning KE. We have recently hired several staff in the area of Financial Mathematics where we expect substantial economic impact through providing improved planning and modelling capacity for financial companies. The Institute for Financial Mathematics (IFAM) is collaborating with a commercial company, Financial Network Analytics (FNA), to develop a software tool for financial analysis, as well as with a large international Insurance, Reinsurance company (Aspen Insurance), to answer risk management questions with reference to risk theory research findings. The work, which was partly supported by a £10,000 KE voucher, will result in improved costing of insurance products.
The Department's approach to Impact is underpinned by strong support from the University, which has a central Business Gateway team dedicated to fostering links with industry and other research users. The DHoD gives regular presentations to members of Business Gateway to apprise them of research activities with impact potential. Business Gateway run regular sessions with the Department to look at possible opportunities for collaboration. They also provide expert advice and guidance in patent applications (see example below). They also run a KE Voucher scheme to support early stages of impact activities; this is being used to support the IFAM collaboration with Aspen Insurance, as described above.

Multidisciplinary research collaborations: The key to our success in delivering impact is our network of active multidisciplinary links both within and outside the University of Liverpool. Such

links are vital for understanding users' needs and fostering knowledge exchange. Our Research Centre for Mathematical Modelling (RCMM) provides pump-priming grants targeted at activities (workshops and research visits) likely to lead to external collaboration. Workshops have frequently gathered participants in large-scale grant applications, leading, for instance, to an EU FP7 Pathways to Industry grant. Here are some examples of interdisciplinary activities:

- The Department works with Veterinary Scientists at the University, a collaboration which has resulted in projects funded by DEFRA and the Veterinary Laboratories Agency (VLA). Recent projects have focussed on Avian Influenza, E.coli and Bluetongue, diseases in farmed salmonids, and one (involving a BBSRC CASE award) on salmonella control. We supply expertise in modelling and statistics to run alongside field trials coordinated by the VLA. The work on avian influenza had an impact on the control measures developed as a consequence of the 2007/8 outbreak. Work on salmonid diseases led to a model that is now used by the aquaculture industry to inform their disease control procedures, a policy impact described in a case study.
- We have developed statistical methods that are used by the Department of Biostatistics to compare the effectiveness of different treatments for epilepsy, underpinning the most recent NICE guidelines and informing health policy across the EU—as described in a case study. Proposals for avoiding Outcome Reporting Bias have also been incorporated in general advice for the framing of all future NICE guidelines and in advice for submitters of proposals to the Health Technology Assessment (HTA) funding body.
- Our Environmental Radioactivity Research Centre (ERRC) provides a unique facility for the analysis of radionuclide levels in lake sediments for dating purposes. Their services are in high demand by other academic institutions and government agencies. The resulting data on environmental change has led to impacts on policy and legislation on pollution (described in a case study).
- The CMIT has projects on dental, neurological and oncological imaging funded by the NHS and EPSRC. It has recently been awarded a £1.3M EPSRC grant to develop innovative non-invasive tissue-imaging techniques in collaboration with colleagues in Engineering and Biomechanics from Durham, Edinburgh and Heriot-Watt. Researchers are exploring possibilities of clinical applications with a Leeds-based medical software company (Image Analysis Ltd). These projects will have benefits for patients as well as bringing efficiency savings to the NHS and commercial benefits for the company. CMIT also have close links with a North West network of neurosurgeons; the team has a NHS-funded CASE studentship on ophthalmological imaging based at St Paul's Eye Hospital, as well as a Knowledge Transfer Network for Industrial Mathematics studentship with Clatterbridge Cancer Centre.There is ongoing collaborations with groups at the University of North Carolina and Brown University on medial structures that offer an innovative approach to medical imaging based on an underlying topological 'skeleton'.
- Research on wave propagation led to a patent on acousto-optical devices and sound/light interaction within photonic crystal fibres. An exciting extension was to contribute to the design of an 'invisibility cloak', which could have applications in earthquake shielding. We worked with the University press office in communicating our findings, which were subsequently publicised in media such as the BBC, NBC, the Telegraph, and New Scientist. Industrial projects with ELKEM (Norway), Rolls Royce, SAAB, Dupont, Nuclear Electric, AEA and SERCO have resulted in non-invasive methods to detect cracks in e.g. pressurised reactor vessels. Similar research has led to improved bridge design, avoiding destructive vibrations (see the Case Study). The latter two applications represent economic impacts for the companies concerned and the societal impact of improved public safety.
- A computer model, developed by P. Gould in collaboration with British Waterways (now the Canal & River Trust) to estimate pleasure boat traffic on canal networks, has been used to help plan the size and location of prospective marinas in order to minimize adverse effects on water resources and aquatic flora and fauna.

Skills Development: Our PhD students and research assistants frequently gain employment in companies in which they use expertise acquired in the Department. Students contribute to research skills in industrial sectors such as Mercedes-Benz (statistical market analysis); HMRC

(Operational Research); Z+F UK Ltd (software for 3-D laser scanning); and Imagination Technologies (computer chip design). We also foster personal links, developed and maintained through research collaboration, with companies such as Unilever, resulting in three recent CASE studentships. These studentships further cement the links between the Department and the company and provide a channel for communication, such as identifying applicable research topics. Our BBSRC Case Student, mentioned earlier, later secured employment with his sponsor, the VLA.

Public Engagement and Outreach: The Outreach Team, during 2011/12 interacted with more than 11,000 children in 70 schools. In addition to providing activities for school pupils and teachers, the Department actively promotes the communication of research to a general audience, such as the annual Barkla lecture, often given by a Nobel Laureate. We have also organised exhibitions on computer images, arising from current mathematical research at the University and elsewhere, at the 2008 British Association Festival of Science and at the University's Victoria Gallery & Museum.

c. Strategy and plans

We believe that potential for impact is a significant feature of all high-quality research. Our goal is to assist in identifying potential impacts, and facilitate and document their realisation. In addition to a long history of supporting individuals engaged in such activities, we have developed a strategic and holistic approach to impact and KE. Our strategy focuses on four principles.

1) Foster multidisciplinary links and centres. Our strong multi-disciplinary links are key to creating impact. The University actively fosters links between departments, which has led to the creation of several research centres. The newly established *Institute for Financial and Actuarial Mathematics* (IFAM) works with the University's *Institute for Risk and Uncertainty*, which brings together experts from engineering, environmental sciences, and computer science. IFAM has recently been awarded more than £600K through EU FP7 to support an international research staff exchange (IRSES) programme on "Risk Analysis, Ruin and Extremes" (RARE), creating a global network linking 150 staff in 12 institutions in areas such as India, Australia, Japan and Russia. In addition, the University has identified a set of seven cross-faculty *Research Themes* addressing fundamental global challenges, in order to facilitate and support multi-disciplinary links within these areas. Researchers from the Department are currently active within the themes of "Living with Environmental Change", "Personalised Health" (for which K. Chen of CMIT acts as Faculty Champion) and "Materials for the Future". We recently held an imaging workshop and a 'Metamaterials Workshop' funded through the latter two initiatives.

Beyond the University, one key means of developing opportunities for Impact is attending conferences which bring together both academic and industry representatives. For instance, a Newton Institute workshop on Medical Imaging led to a productive partnership between our CMIT and the software company Image Analysis Ltd (see earlier).

2) Popularise research through outreach and public engagement. We are committed to raising awareness of current mathematical research, both through contacts with schools and through activities aimed at the mathematical public. We have created a strong outreach team, now led by two permanent staff, which has a nationwide reputation for its inspirational educational material (the Mathematics Roadshow model developed with the Liverpool Mathematical Society and used across the UK). The team has received funding through four EPSRC Partnership for Public Awareness (PPA) grants. We plan to hire a dedicated staff member to assist with effective communication of our research.

3) Support Impact and Knowledge Exchange through organisational structures. The Department has an effective policy to enable staff to have prolonged periods of study leave in which to establish the contacts necessary to promote impact. This has enabled researchers to build the relevant contacts for the computer vision work referenced above. We shall also use the annual Professional Development Review to explore opportunities for impact, as well as put in place plans to realise these opportunities and monitor individual success. We shall arrange for regular staff development sessions, run by staff with a successful track record in impact, and

arrange for them to act as mentors to staff with early-stage impact.

4) Involve end-users in the research and impact process. Workshops funded by our RCMM pump-priming grants (above) frequently involve end users of our research, resulting in a better focus on their requirements. Several of the impacts listed in (b) exemplify this approach: Three of our Industrial Workshops involved the end-users of our crack-detection methods (above) together with colleagues from Engineering. The project manager of SERCO (one of the end-users) gave presentations explaining their practical requirements. End-users of our bridge design Case Study have visited the Department for prolonged periods (in one case funded through the EU "Pathways to Industry" grant mentioned earlier), leading to innovative bridge component design informed by targeted mathematical research: a marriage of theory and practice which would be impossible without such close cooperation. Finally, NHS staff are actively involved in the whole process of CMIT imaging research.

d. Relationship to case studies

The submitted case studies exemplify our strategy of encouraging collaborations (both academic and with the end-user) as a major route to impact and to demonstrate its efficacy. The Case Study on "Informing treatment decisions after single seizures and for newly diagnosed epilepsy" was a result of co-operation with the Dept. of Molecular and Clinical Pharmacology; the Case Study on "Control of epidemics in the aquaculture industry of England and Wales" is a result of collaboration with the Department of Veterinary Science; the Case Study on "Meta-material structures and routing of elastic waves in engineered structures" involves links with the end-user as well as the Institute of Photonics at the University of Sydney and the Engineering School at LJMU; and the Case Study on "Radiometric dating of environmental records in natural archives" has involved collaborations with groups at the US Environmental Protection Agency, University College London Environmental Change Research Centre, the University of Rhode Island School of Oceanography, and the US National Parks Authority.