Institution: The University of Edinburgh/Heriot-Watt University (Maxwell Institute)

Unit of Assessment: B10, Mathematical Sciences

a. Context

The Maxwell Institute for Mathematical Sciences (MI) was established in 2005 by the University of Edinburgh (UoE) and Heriot-Watt University (HWU) and integrates the research activities in mathematical sciences of UoE's School of Mathematics and HWU's School of Mathematical and Computer Sciences.

The MI holds strongly to the principle that there are no bounds to the domains in which mathematics can have impact and we view the population of users (current and future) of our research as being similarly broad. Accordingly our research generates impact in areas that may be expected, given the distinctive research expertise of the MI, but also in areas in which mathematical impact may come as a surprise to some. Examples of the former include the impact of our research in actuarial and financial mathematics on the insurance and finance industry, and the impact of our research in mathematical ecology and epidemiology on the work of environmental and disease-control policy makers. Examples of the latter include the impact of our work on the mathematical modelling of homeless populations on social housing policy and the influence of our statistical research in forensic science and the law. Our strategy is aimed at generating both economic impact and impact on public policy and the quality of services, as these examples illustrate; it also prioritises public engagement as a means of disseminating the benefits of mathematical research across society.

b. Approach to impact

Key sectors

Our research excellence across the spectrum of mathematical sciences enables us to impact on many distinct sectors. Since 2008 our main contributions have been in the following areas.

Finance and Insurance. With extensive expertise in stochastic modelling and in actuarial and financial mathematics, the MI generates a continued and growing impact on this sector. Our links with major players in the industry have considerably expanded with the foundation in 2010 of the Scottish Financial Risk Academy (SFRA), a consortium funded by industry and the Scottish Funding Council (SFC) that brings together the MI and several major companies (Lloyds Banking Group, Aberdeen Asset Management, Moody Analytics) to address the most pressing issues facing the financial sector. Building on this success, the MI has recently established the Actuarial Research Centre (ARC) with £400k of funding for PhD scholarships provided by the Institute and Faculty of Actuaries.

Biological and Life Sciences. We have strengthened our interactions with these sectors; 12 MI staff now work in mathematical and statistical biology and ecology. Beneficiaries of their research include healthcare professionals and managers, environmental organisations and policy-makers, and disease control agencies. This is exemplified by Antal's work on pancreatic cancer (published in Nature and reported by the BBC, New York Times and many other media organisations), by Gibson's research on the dynamics of *C. difficile* in hospital wards which underpinned new infection-control strategies, by Painter's work on cell adhesion in tumour development, and by White's research on competition between grey and red squirrel populations.

Energy and Climate Change. Since 2008 we have actively sought to generate impact in this sector through collaboration with strong engineering groups with connectivity to the user community. Significant projects include a major EPSRC-funded initiative led by Foss for the MI and involving the National Grid on the mathematical foundations of energy networks, an SFC SPIRIT scheme that provides mathematical and statistical modelling support to the electricity

industry within Scotland (Zachary), and an EPSRC-funded project on the prevention of blackouts (McKinnon, Gondzio). Close links with HWU's Institute of Petroleum Engineering have led to improved numerical algorithms for oil-reservoir modelling (Lacey, Lord, Duncan). Supported by EPSRC funding we have also worked with building engineers and stakeholder groups such as the Chartered Institute of Building Services Engineers (CIBSE) on numerical algorithms for predicting building energetics under climate-change scenarios (Gibson, Patidar).

Public engagement and education. Engaging with the public to communicate our research is a priority for the MI. Building on a strong tradition of outreach events dedicated to school children, we have developed a series of activities targeting a wider public. Examples include regular exhibitions at the Edinburgh International Science Festival ('Forensic Statistics' in 2012 attracted over 3500 visitors, 'Symmetry' in 2013 attracted over 4400), the Möbius exhibit (which makes the concepts of non-orientable spaces accessible to a broad audience), and the contribution of MI researchers to a series of 1-min videos explaining their work. The International Centre for Mathematical Sciences (ICMS) further enhances the public visibility of mathematics in Edinburgh by running a series of outreach events, including public lectures centred on its workshops' themes. The MI has pioneered the use of computer-based learning, leading to the development of the SCHOLAR programme (http://scholar.hw.ac.uk) which by 2012 had developed to cover 90% of the Scottish senior-phase secondary school curriculum. SCHOLAR is now used in the vast majority of Scottish secondary schools and has been adopted throughout the world, widening access to mathematical training.

Other sectors. The impact of our research extends well beyond the sectors highlighted above. For example, the Operational Research and Applied & Computational Mathematics groups have consistently delivered novel methods and algorithms that are adopted in commercial and open software and benefit industrial sectors such as the food industry or chemical engineering. This has led to sustained interactions with industrial partners including Accelrys, SAS, Yahoo, Orange-FT, Arup, Statoil, Format International and Selex Galileo. Pure mathematics contributions are exemplified by the exploitation by computer scientists of a result by Carbery and Wright on norms of polynomials over convex bodies, and by the implementation in Maple of an algorithm for the computation of curve intersections proposed by Smyth and his PhD student Hilmar. Our impact is also achieved through the high-level training we give to our research students; a prominent example of this is the consultancy ThinkTank Mathematics, founded by former PhD students and active in sectors such as energy and finance.

A supportive environment

We seek to provide an environment that generates impact by offering support and training to our staff and by encouraging good practice.

Direct involvement with users. The establishment of the SFRA and ARC exemplify our approach of creating structures that promote direct interactions between our staff and potential users of their research. Other initiatives include the ERGO forums – regular networking events run by the Operational Research group with prospective industrial partners (such as RBS, the Student Loans Company, AF-Mercados) – and the networking events of the centre for Numerical Algorithms and Intelligent Software (NAIS). The MI was a partner on an EPSRC UK Mathematics-in-Industry Study Groups award (2008–2012) for a series of workshops to bring together mathematicians and industrialists to work on real-world problems, hosting a workshop in 2008 which included participants from energy (National Grid) and telecommunications (Motorola).

Interdisciplinary research. We recognise that the impact of mathematics in other sectors is best delivered through collaborations between mathematicians and researchers from other disciplines. The expansion of interdisciplinary research is therefore at the centre of the MI's impact strategy. This involves maintaining a large fraction of staff working at the interface between mathematics and other disciplines and taking a leadership role in interdisciplinary projects such as Painter's interaction with the Roslin Institute on networks and pattern formation. Around 40% of MI staff

describe their research as lying at the interfaces with disciplines ranging through the physical, biological and medical sciences, engineering, computer sciences, business, finance and law. The depth of our contribution to some of these disciplines is reflected in the submission of 9 MI staff to UoAs 19 and 20.

MI staff are encouraged to lead interdisciplinary activities. For example, HWU's initiative to grow research capacity at the Life Sciences Interfaces was initially led by Gibson. This helped to ensure recruitment in the life sciences that targeted researchers with records of successful interaction with mathematics, brought about new collaborations between MI mathematicians and cell biologists on intracellular processes, and led to a UoE/HWU partnership supported by a MRC Confidence in Concept award, which is now providing new opportunities for impact. Another example is the Maximaths scheme launched in 2011 to stimulate collaborations between MI mathematicians and researchers from other departments; so far, it has provided financial support to 15 projects on topics that range from porpoise echo-location to computer-aided design and has led to multidisciplinary grant proposals. Similarly, the MI is leading EM^3 (Edinburgh Multidisciplinary Multiscale Modelling), a grouping stimulating interactions between science departments through its workshop and visitor programmes.

MI and ERPem. We seek to exploit our membership of the broader Edinburgh Partnership for Engineering and Mathematics (ERPem) which places us ideally to interact with Engineering. This strategy has led to several joint projects with engineers (e.g. on oil reservoirs, wave power, porous and granular media, building simulation, energy supply and storage) supported by joint grants (e.g. EPSRC Bridging-the-Gaps 2006-10). Our interactions with engineering in turn enhance our linkage with industry from SMEs to large companies. An example of this is the involvement of AGR Petroleum, BLOS International, CMG, NDA, Quintessa, RPS Energy, Schlumberger and Total in the MI-led UK network Porous Media Processes and Mathematics. The MI's capacity to deliver impact in areas such as porous media and energy will be further enhanced through our involvement in the £17M Sir Charles Lyell Centre for Earth and Marine Science and Technology, funded by NERC, SFC and HWU and due to open in 2015.

Support for impact. Since 2008 we have expanded the systems that support MI staff in generating impact. All staff now benefit from the services of two dedicated Business Development Officers whose remit includes engagement with industrial partners and other research end users. This was made possible by the award in 2009 of the Converge Project, a £6.5M knowledge transfer initiative, jointly funded by the European Regional Development Fund, EPSRC and HWU, which provides a Business Development Officer for MI staff in addition to a range of other support mechanisms. Our successes with infrastructure grants have enabled further investment in this direction: the EPSRC-funded NAIS and ICMS jointly fund a Knowledge Transfer (KT) Officer who coordinates events with potential industrial users. Similarly, the SFRA has a dedicated KT professional who supports the interactions between the MI and the financial sector. We have enhanced support for Public Engagement (PE) activities by funding a full time PE Officer at UoE (from 2011 on); she leads an Outreach Team involving about 15 staff and students and coordinates the MI's PE web presence. In addition to this local support, MI staff benefit from the universities' wide range of specialist services provided through HWU's Research & Enterprise Services (RES) and UoE's Edinburgh Research & Innovation (ERI). RES and ERI support the MI in formulating research programmes and in identifying strategies and mechanisms for exploiting research outcomes to generate impact. They also provide expert assistance on commercialisation – including licensing agreements, patent applications and the formation of spin-out companies – and on wider forms of knowledge exchanges including consultancy. Since 2012 the MI also benefits from EPSRC's Accelerating Impact Accounts associated with an investment totalling £3.8M for both universities to support interactions with industry and other end users of research.

Training. Guidance on impact generation is available for all MI staff. For example, ERI run courses on 'Writing Pathways to Impact' tailored for mathematicians that help staff maximise the benefits of

impact activities funded by RCUK grants. Leadership programmes on both campuses provide training for researchers at all career stages in research techniques and in approaches to delivering and enhancing impact. Early-career researchers are particularly encouraged to take these training opportunities and to participate in the award-winning Scottish Crucible Research Leadership Programmes. These enable participants to become more collaborative and interdisciplinary in their approach to research; to discover new skills and attitudes that can enhance the innovation inherent in their research; and to develop their understanding of how research impacts on society through the process of Knowledge Transfer.

c. Strategy and plans

With its broad research portfolio, strengths in many areas of applied mathematical sciences and strong collaborative links, the MI is well placed to address the challenges posed by impact generation for mathematics research centres. Our strategy and plans aim both at increasing our impact in those areas where we have an established track record (exemplified by our case studies) and at achieving impacts in new areas, particularly related to research areas that have emerged within the MI during the reporting period. We first highlight examples of the areas where we will strive to generate new impacts in the next 5-10 years.

Priority areas

Ecology and Epidemiology. Our extensive ongoing collaborative links with these disciplines (White, Antal, Gibson) offer excellent opportunities to generate impact in the medium-term. For example, from 2013 we collaborate in a new BBSRC-funded initiative on ash dieback which aims, as a matter of urgency, to design measures to control its spread. Our statistical modelling will underpin the control measures and should generate almost immediate impact. Similarly, our continued excellence in wildlife population modelling should extend our impact on policy for controlling invasive species.

Financial Risk. The financial sector remains volatile in the wake of the 2008 crisis and, as regulatory mechanisms adapt and develop, so will the demand from the financial industries for improved tools for quantitative prediction of risk. Industrial partnerships such as the SFRA and the ARC and our strengths in financial risk (Cairns, McNeil) place us in an ideal position to respond to this demand through provision of new products, consultancy, and other mechanisms. These links also enable us to anticipate the major issues that the financial sector will face and hence to identify the directions for current research most likely to generate impact in the near to midterm. In the longer term, we expect our research in financial mathematics (Gyongy, Rasonyi, Sabanis, Szpruch) to make strong contributions on par with Gyongy's work on the mimicking of random processes, now exploited by quantitative analysts worldwide.

Numerical algorithms and simulation. Delivering impact from major initiatives such as our S&I award on Numerical Analysis and Intelligent Software will be a priority for the MI. For example, Leimkuhler's work with Accelrys exemplifies how cutting-edge mathematics can advance commercial molecular simulation packages and, with the dedicated KT resources available to NAIS, further impacts of this nature should be expected.

Energy and Climate Change. With our portfolio of funding for both research and knowledge transfer in these areas and the involvement of industry and professions, we expect significant impact to accrue, for example, through the implementation by power companies of measures for improving robustness of energy supply networks, or the widespread adoption by building design engineers of software tools incorporating predictive models arising from our research. We will exploit our position as a member of ERPem, in which energy is a principal theme and we will participate fully in local groupings and networks such as HWU's Energy Academy and UoE's Edinburgh Centre for Carbon Innovation, to ensure that the MI makes the most of opportunities for generating impact for mathematics in the energy sector.

Mechanisms to realise our potential

To facilitate delivery of these goals we plan to adopt the following measures.

- We will strengthen our links with research end users by supporting new efforts in networking with industry. The SFRA provides a template for this and we will extend its innovations, such as its 'industry colloquia', to other sectors.
- We will extend our capacity at the interface between mathematics and other disciplines by recruiting staff with research interests that cross disciplinary boundaries (continuing the successful strategy that has seen the recruitment of Antal, Branicki, Goddard, Lindsay, Leinster, Maddison and Szpruch since 2008);
- All staff will be encouraged to identify and exploit opportunities for interdisciplinary research. The series of interdisciplinary workshops organised under our Bridging-the-Gaps award proved an excellent mechanism for initiating such collaborations and this model will be adopted to run similar events with our partners in ERPem and with other disciplinary groups. Early-career staff will be encouraged to participate in networking events such as those organised under the Crucible Programmes.
- We will maximise the benefits from our dedicated support staff (2 Business Development Officers, 1.5 Knowledge Exchange Officers, 1 Public Engagement Officer) and make full use of other available sources of institutional support for Knowledge Transfer (for example through the Converge project). This support will provide all MI staff with training and guidance on Knowledge Transfer and commercialisation, including mechanisms not extensively used by the MI hitherto such as the formation of spin-out companies.
- We will enhance our efforts in Public Engagement, in particular through the newly created outreach team, and we will ensure that MI staff take full advantage of our membership of Beltane, a PE network that offers PE fellowships and other PE training opportunities.

d. Relationship to case studies

The case studies submitted, with their wide variety of delivery mechanisms and target sectors, reflect the breadth of our approach to impact. They also informed some of the measures that we propose to realise fully our potential for impact in the future.

The 4 case studies from Cairns, McNeil, Currie and Radcliffe on modelling mortality, financial risk and response to marketing illustrate the obvious benefits of maintaining ongoing collaborative arrangements with a particular industrial sector. By ensuring that all MI staff with relevant interests participate fully in networks such as the SFRA we expect to see further case studies of this nature emanating from a wider range of staff in the future. The case study by White – on the use of mathematical models that underpin measures to protect the red squirrel population – and that of Gibson – on the control of hospital infections and of plant epidemics – reflect the prior experience of both these researchers: they worked outside academia in multidisciplinary environments where they established the collaborative networks through which the impact of their research since joining the MI has been delivered. We are therefore confident that the strategy of further recruitment of staff with interdisciplinary interests is wise. Two case studies (Leimkuhler, Gondzio) are related to the implementation of new algorithms for simulation or optimisation of complex systems in commercial packages. Our increase in research capacity in numerical algorithms resulting from NAIS clearly indicates that the numerical software industry is one that should be targeted under our strategy. The case study by Aitken – on the use of Bayesian reasoning in the interpretation of forensic evidence – illustrates the importance of encouraging academic collaborations with other disciplines (in this case forensic science and the law). Our strategy of being proactive in organising networking events with other disciplines will develop further multidisciplinary impacts of this nature.