Institution: University of Warwick

Unit of Assessment: 10 Mathematical Sciences

a. Context

[Convention: Staff names in *italics* are not submitted to this UoA.]

Past and current impact areas for the two departments include medicine and health care, finance, engineering, media and market research, government policy, security, education, law, energy, agriculture, risk and safety, and the public appreciation of science. Beneficiaries include national and international companies, governments and policy makers, and the general public.

Some of our impact arises naturally from research in areas where we are strong and which have points of close contact with applications, including: financial mathematics; computational, medical and methodological statistics; applied Bayesian modelling; mathematical and systems biology; epidemiology; number theory; and numerical analysis. Some arise more from individual research projects that may not, at the outset, have promised a significant impact. And some, such as work in the public appreciation of science, arise from the confluence of our research with particular skills or interests of individuals.

b. Approach to impact

The nature of much research in mathematics, and to a lesser extent statistics, means that impacts are often long term, so that in many of the case studies, the explicitly demonstrable impact is just the tip of the iceberg. Our approach to impact involves: (i) **direct engagement** with non-academic research users on particular projects, (ii) **structural engagement** (direct or indirect) with research user communities where there is the potential for impact in the future; and (iii) the vigorous **dissemination** of our research to appropriate research users, in particular the non-mathematical scientific community both within universities and beyond. We believe that the last of these is, in the long-run, as important as the first two in generating meaningful impact in the mathematical sciences. Our approach during the period 2008-2013 includes many examples of all three types of activity.

Staff interact directly with key users and beneficiaries in several ways. A major one is through RISCU (Risk Initiative and Statistical Consultancy Unit) which undertakes risk analytic and statistical consultancy across the public and private sectors. RISCU establishes contacts, and stimulates and motivates research. It strongly encourages and supports engagement of staff with industry, with particular support for the activities of young researchers across both departments. RISCU's work is wide-ranging in nature, typically avoiding routine consultancy, but seeking applications that draw on the latest research and those likely to stimulate further research. For instance, applications of change-point analysis in high dimensional time series with high frequency of observation, or problems needing recent developments in MCMC algorithms to achieve reliable solutions in feasible time. We have worked with the Home Office to develop Bayesian Network Software to evaluate efficacy of *Prevent* (counterterrorism) policies, with the Nuclear Decommissioning Authority to develop protocols for involving stakeholders in complex decision and risk analyses, and with water industries and, more recently, London Underground, to develop world-class asset management methodologies. Other major contracts, involving top research academics from Statistics, have been with: Unilever, the Forensic Science Authority, the Medical and Healthcare Products Regulatory Agency, the National Grid and the UK Atomic Energy Authority. Recognising the increasing importance of RISCU, we appointed *French* (from outside Warwick) as Director of RISCU in 2011 and he has developed RISCU's activities both within and outside the University to increase the engagement and knowledge transfer functions alongside more conventional consultancy. Since his appointment, *French* has brought in new consultancy with government departments and agencies (e.g. the National Development Agency, the Medicines and Healthcare products Regulatory Agency, and the Department of Health), which are leading to policy impacts.

In 2012 our successful mathematical epidemiology group formed an interdisciplinary centre, the Warwick Infectious Disease Epidemiology Research Centre (WIDER), partly to facilitate better interaction with research users and external public health organisations. Keeling directs

the Centre, and his work with colleagues (including House, *Danon*) on the modelling of influenza led to one of our case studies and his role in advising the World Health Organisation (WHO) and the UK Department of Health. Another case study involves animal health (including *Tildesley*'s research on foot-and-mouth disease), and this work has involved engagement with researchers and agencies in the USA, Japan, Turkey, and Australia. In 2012 WIDER was able to take advantage of the university's strategic alliance with the Liverpool School of Tropical Medicine (LSTM), and *Hollingsworth* was appointed to a new post jointly between Warwick Mathematics and the School of Life Sciences, and LSTM. WIDER, with the support of the two departments, is now bringing novel modelling and statistical inference techniques to a broader set of problems and addressing important and challenging problems in the public health arena (through Public Health England, and the Health Protection Research unit) and developing funding and greater expertise in the study of Neglected Tropical Diseases.

Staff in the two departments are also closely involved with the Warwick Systems Biology centre (WSB). Research projects with potential impact include van den Berg's collaboration with a Cardiff-based immunologist on T-cells that target tumours.

In Statistical methodology, we are strongly committed to the development and publication of fully documented software packages, often as part of R, Matlab and other platforms. Recent examples include: Roberts and Keeling in a BBSRC project in close collaboration with Defra, have developed a graphical user interface for visualising Bayesian analysis of farm-based epidemics for use in guiding control policy in the event of an outbreak; our staff currently have more than 15 packages published on the CRAN and Bioconductor worldwide repository networks based on departmental research; and Aston's SSModels software, for inference using state-space models, which is known to have been downloaded over 17,000 times. We are very active within the R project, and hosted the 2011 UseR! conference which attracted over 450 delegates from within and outside academia. Aston serves as an external member of the Government Statistical Service Task Force on X-13-ARIMA-SEATS, with his recommendations being accepted such that new software is being rolled out to analyse all UK government time series. In Mathematics, Dedner is a core developer of DUNE (The Distributed and Unified Numerics Environment) which is a modular toolbox for solving partial differential questions using grid-based methods with special emphasis on parallel computing using distributed grids. DUNE is open source and has a growing user community. DUNE is supported by Statoil. At present the main users of DUNE are researchers in applied disciplines, but support for non-academic users is available and there is potential for significant impact in the longer-term.

The departments work to stimulate public interest and engagement in the mathematical sciences through both collective and individual activities. A very popular public lecture series has been running since 2010; the twice-yearly lectures (usually but not always bringing in external speakers) regularly attract over 200 participants. A public session of the European Conference on Complex Systems 2009, on the Complexity of Global Change, attracted participants from city and county councils and other general public. We are participating with the Warwick Arts Centre in the Arts Council funded project *This is Tomorrow,* which brings artists into the departments to explore the role of mathematical sciences in issues of major public interest, and which is intended, in due course, to lead to the production of significant art works. We enhance mathematical sciences related education in schools by hosting the flagship node of the government-funded Further Mathematics Support Programme (which grew from an earlier Warwick programme) and by running weekend masterclasses for schools. Individual staff members write popular books and articles, and appear on TV and radio; see, for example, the case studies by Stewart and by Series and Schleimer. Our staff are given both the opportunity and encouragement to engage in these activities.

Individual staff have contacts and projects which have or may lead to impact. For example: staff have previous and/or continuing relationships with the Heilbronn Institute; MacKay was a co-I on a Technology Strategy Board (TSB) project with Metris UK on a coordinate measuring robot, and is involved in the Global Collaboration on Financial System Stability, coordinated by Sciteb (a consultancy in London) and involving the Bank of England, the former Financial Services Authority, the China Banking Regulatory Commission, and several large banks.

Other interactions with key users occurred through structural engagements. Examples include the industrial fellows associated with CRiSM, a visiting fellow, Ian Hall, to the Centre for

Complexity Science, and industrial membership of advisory boards for both Programme Grants and CDTs (see below). Such interactions seed a mutual growth of understanding and the building of relationships which lead to the development of projects producing impact.

A wide cross-section of staff have interacted with, engaged with, or developed relationships with key users and beneficiaries through the following mechanisms:

(a) CRiSM (the EPSRC funded Centre for Research in Statistical Methodology) has two industrial fellows, Tim Davis and Tony O'Hagan both of whom have strong links to industry. CRiSM has organised 22 workshops within the period, and hosted over 1000 visitors since 2008. The CRiSM workshop in 2011 on "Inference for Epidemic Risk" attracted speakers and delegates from Defra, NHS, the farming industry, as well as academics from mathematics, statistics, and the biological, medical and veterinary sciences. "Statistical Models for Epilepsy Data" was targeted at practicing clinicians as well as academic and non-academic medical statisticians. Other examples of CRiSM workshops which have had substantial industrial and/or governmental involvement are: "Graphical Models and Genetic Applications" and "Inference for Infectious Risk".

(b) The Mathematical Interdisciplinary Research at Warwick (MIR@W) programme was established in 1997 and engages the two departments with research activities in 10 others disciplines and broadens awareness of potential synergistic applications. MIR@W organises a series of interdisciplinary one-day meetings in Warwick (61 during the period), many with industrial participants, and acts as a vehicle for interdisciplinary research and PhD training.

(c) Engagement through doctoral training: The existing Complexity Science and MASDOC DTCs have models for engaging with real world problems; these include industrial participation in research study groups and supervision of joint projects. During the period students in the Centre for Complexity Science (CCS) CDT have undertaken Masters projects co-supervised by British Antarctic Survey (BAS), Arithmatica, NHSIII, Jaguar Land Rover (JLR), BT, GlaxoSmithKline (GSK), Sciteb, National Grid, Netherlands Cancer Institute (NKI), Thales, NHS W Midlands, and Mercedes F1. PhD project supervisors include NKI, Siglead, BAS, Sciteb, and Pirbright. The CCS CDT Advisory Board includes members from Network Rail, NHSIII, JLR, Tesco, Sciteb and Unilever. CCS research students have been recruited by Manufacturing Technology Centre, Citibank, Mercedes F1, MRC Biostatistics unit, NKI. The award of two new CDTs, MathSys and OxWaSP, will give us the opportunity to further develop our links with industry and government through our doctoral programmes. MathSys is already supported by 13 external partners. OxWaSP partners and collaborators include Amazon, Deepmind, FERA, GlaxoSmithKline, Google, Lubrizol, Illumuna, MAN Investments, Millward Brown, Novartis, Optimor, the Office of National Statistics, Unilever and Xerox.

(d) Engagement through the Advisory Committees of major research grants: EQUIP is concerned with statistical inverse problems arising from the earth's subsurface and its Advisory and Impact Board has representatives from BG (formerly British Gas), the Atomic Weapons Establishment, and the UK Met Office – the recent launch event attracted additional industrial partners (Alston Power, British Petroleum). *I-like* has representation from GlaxoSmithKline.

A recent example of the departments' agility occurred when responding to the EPSRC 2012 funding call, *Future Manufacturing with Mathematical Sciences*. Whilst this was a call to fund cross-disciplinary research, there was/is potential for future impact, and we did not have pre-formed ideas of how to respond. An initial briefing from the EPSRC Mathematical Sciences team was organised with colleagues from WMG (Warwick Manufacturing Group). Connaughton and *Nichols* then led a series of discussions and organised a MIR@W day. After some months, two bids were made (jointly with researchers from WMG) and one, related to 3-d printing, was successful (Kendall et al: *Inside-out: Statistical methods for Computed Tomography validation of complex structures in Additive Layer Manufacturing*). In addition, Connaughton applied for and was selected to join the EPSRC Early Career Forum in Manufacturing Research. Building on their experience, Connaughton, *Nichols* and Theil organised a Newton Institute Turing Gateway to Mathematics meeting: *Stochastic and Statistical Models at the Interface of Modern Industry and the Mathematical Sciences*, in March 2013, with representatives from academia and industry.

The departments have enabled, supported and rewarded staff contributing to impact by

providing administrative support and other resources to support impact activity in a direct way, and by appropriate changes in duties. Examples include: (i) *Hutton* had a significant reduction in other duties because of her extensive impact work (which has led to two of our case studies); (ii) Zaboronski, following on from a Royal Society Industrial Fellowship (2004-2008), was granted 50% unpaid leave (2008-2012) in order to facilitate his continued collaboration with a Japanese company on high density hard disk coding – during this period he worked 50% for the company and set up a European subsidiary based in Warwick. The University's Research Support Services assisted with drawing up necessary contracts.

The University's 10 Global Research Priorities (GRPs) provide a strong focus and internal resource to support impact. Each GRP is focused on a major research challenge and they promote interdisciplinary research, the development of critical mass, and strong external engagement with government, industry and society. The departments have particular involvement in the GRPs in Food Security (Smith is one of the leaders), Innovative Manufacturing (Connaughton, Kendall, Theil), Science and Technology for Health (Keeling, House, Roberts), Energy (*French,* MacKay) and Behavioural Science (MacKay). Dedicated business engagement support is provided to each of the GRPs through the University's Corporate Relations Unit (CRU) and they promote interaction and partnership with important external stakeholders. In addition, institutional HEIF5 funds have been provided to seed new impact-related activity through the University Impact Fund.

Other approaches include: participation in established Study Groups with Industry – *Wood* organised the European Mathematical Study Groups with Industry at Warwick in 2010, which included problems from Teknova, Selex Galileo, Lloyds of London, AIR worldwide, 61-54 Design, TalkTalk and Syngenta; involvement in interdisciplinary projects like IMAGES (Integrated Market-fit and Affordable Grid-scale Energy Storage), NIBS (Network on Integrated Behavioural Science), EINS (European Internet Science); participation in Academic-Industry events such as those organised by the EPSRC (Complexity and Energy, Maths and Manufacturing) and an Industrial Maths KTN UK-Japan robotics research day.

c. Strategy and plans

Mathematical sciences permeate and underpin most of the rest of science, medical research, and social and economic research. Impact areas are thus very broad, unpredictable and diffuse. Recognising this, we have a very broad-based strategy which seeks to maximise impact as quickly as possible.

Central to this is our vibrant research environment and open research culture, which continues to strengthen links between different areas of the mathematical sciences, and supports the creation of, and maintenance of, many interdisciplinary research centres and research activities as described above and in our REF5. We intend to exploit the many positive aspects of our environment to improve our performance in the area of impact.

We will work across the university in "big data analytics" with the goal of establishing an international Data Science Institute to develop solid theoretical underpinnings of data analytics. Scoping meetings are being held, and we have introduced a BSc degree in Data Science for first entry in 2014.

We will appoint a new or existing staff member to be the Impact Liaison Officer (ILO) for the Mathematical Sciences. This will build on the appointment of *French* as Director of RISCU, and the appointments of Theil as Industrial liaison for MASDOC and Connaughton as External partners liaison for the new MathSys CDT. (Complexity Science has *Nichols* as Business, Industry & Government Liaison officer since 2011). Amongst the ILO's duties will be engaging with the KTNs, and with the Catapult centres, specifically in High Value Manufacturing, Connected Digital Economy, and Future Cities, and also with the recently launched one in Transport Systems and the expected one in Energy. Internally to the University, the ILO will liaise with Warwick Ventures, the University's technology transfer office, and the CRU to ensure staff in the departments are properly informed about procedures and opportunities for exploitation of IP, spin-out companies, etc.

The RISCU consultancy has established a successful template for industrial involvement and we plan to develop this to cover a broader range of staff within the two departments.

In appointing academic staff, the capability of a candidate to make substantial impact outside academia in their work will be explicitly taken into account in the appointing criteria (Statistics has done this since 2012) and we will continue to make appointments to strong candidates who score well against this criterion.

We will always take an active leadership role in cross-university initiatives (including the GRPs) which have mathematical and statistical research as key ingredients. In all cross-disciplinary research, we will ensure that the mathematical research aspects of the project are prominently represented (examples in section (b) above). We are systematizing our contact with alumni (especially PhD students who move into positions outside academia), providing information about our developing research portfolio.

Wherever appropriate, we will continue to include academic and non-academic users of our research and training in advisory capacities for our major research initiatives and CDTs, and to otherwise nurture external contacts, often but not always facilitated through RISCU, MIR@W, and the CDT programmes.

Encouragement and support for staff to engage in activity increasing the public awareness of mathematical science will continue; we will develop further the training for our PhD students and junior staff in this area.

We will continue to pursue a strategy of high-profile and rapid dissemination of our research as demonstrated through conventional publication, software development, websites, and our many and varied conferences and workshops.

d. Relationship to case studies

The research behind our submitted case studies pre-dates our current impact strategies. Nevertheless, our case studies are in line with the current strategy, and in many of them, clear growth lines to the case studies can be seen from precursors of our current strategies formed 20 or 30 years ago. As part of the reflective process of preparing for this submission, we have noted the importance of identifying research likely to have impact at an early enough stage so that interest (in the impact) can be maintained, progress can be logged and evidence collected (rather than just releasing our ideas for others to use and moving on with the associated research).

The creation of software to support the rapid, effective and broad-reaching dissemination of research has been a crucial factor in the impacts created in in the bio-technology, public broadcasting and finance industries (respectively B10.1, B10.3 and B10.8).

French and Smith are maintaining research and knowledge transfer activities related to nuclear emergency management (B10.4) through an EPSRC research grant in collaboration with the Indian Atomic Energy Authority, doctoral projects and active membership of NERIS, a European network of researchers, emergency managers, regulators, operators and communities dedicated to enhancing planning of response to radiation accidents. Hutton (B10.5, B10.6) is active in promulgating and extending her work, developing chain event graphs and ethical but robust approaches to missing data.

On public engagement, the departments have a long history, beginning with Christopher Zeeman, his Royal Institution Christmas lectures in 1978 and his mathematics masterclasses which started in 1981. Stewart, Series and Schleimer have followed his example, each in their own way, leading to two of our case studies (B10.9, B10.10).

The Mathematics department decided to invest explicitly in applied mathematics from around 1995. MIR@W was set up in 1997. Its Mathematics in Medicine initiative, started in 1998, developed eventually into the Systems Biology Centre with its current links to Cancer Research UK, Syngenta, Xenologiq, Unilever, University hospitals Birmingham and others. MIR@W also supported the growth of cross-departmental research in epidemiology which is now formalised as the WIDER group, with strong links to public health authorities and advisory roles in government from which two of our case studies developed (B10.7, B10.11). One of our case studies stems from a more recent move to develop a group in number theory (B10.2).