Institution: University of Aberdeen

Unit of Assessment: 10 (Mathematical Sciences)

a. Context

The Institute of Pure and Applied Mathematics (IPAM) at Aberdeen comprises research groups in various areas of mathematics. One of the most active groups in the development of impact, only created in 2005, is the group specialising in dynamical systems. This area of mathematics lends itself to achievement of impact through applications and methods in *model-based data analysis* and *data-based modelling* which we exploit to address challenges especially working with other disciplines. An example of the interaction between the Pure and Applied research in IPAM is the joint publication of Robinson and **Thiel,** which established the theoretical foundations of the results in the third Impact Case Study.

Recent research at IPAM on *model-based data analysis* and *data-based modelling* resulted in novel mathematical techniques in time series analysis which allow evaluation of interactions between constituents of networks and the direction of the information flow. The research has applications in a wide range of engineering challenges as well as in other academic disciplines. As a result, we contribute to the work of other disciplines, in particular medicine and life sciences, and successfully influence pathways to impact in their own research agenda. Presently, the main non-academic beneficiaries of our research are in the medical and biotechnology sectors, with commercial impact and impact on research & development groups. Other research interests within dynamical systems, for example in chaos theory, yield impact within fields such as engineering.

We also develop impact on society, culture and creativity, especially through public engagement. Since 1976 IPAM has been coordinating the Scottish Mathematical Challenge competition for schools in the North of Scotland (http://www.wpr3.co.uk/MC/), with 472 pupils from 34 schools taking part in 2012/13. Members of IPAM also deliver public lectures on various applications of mathematics. These have included **Benson**'s lectures on "*Mozart, Maths and Mechanics*" at the Music Hall in Aberdeen in 2009 (c. 600 attendees), and "*Symmetry in Music*" at MSRI, Berkeley in 2013 (c. 200 attendees), as well as various contributions by **Thiel**, including "*Dating Poems with Mathematics*" in the Word Festival, Aberdeen 2009 (c. 70 attendees), two selected contributions to the British Science Festival 2012 "*The War Within Us: How Biologists and Mathematicians Team Up to Fight Diseases*", and "*Mathematics and Crime*" (each with c. 40 attendees), and a series of lectures at Albyn School, Aberdeen (2011-2012).

Several findings from our research projects have been reported in the press including The Guardian, The Times, The Daily Telegraph, and The Economist; as well as broadcast media, such as BBC Radio 4 and BBC's main website. Exemplar interviews include our research on the mother-foetus heart-beat synchronisation (Case Study 3), and on the results from our mathematical models on human pathogens.

b. Approach to impact

Engagement with key users and agility in response to new challenges. Our key end-users, with whom we routinely collaborate, are researchers in medical sciences and professionals in the medical sector. We have close relationships with healthcare groups, for example the Groenemeyer Institute in Bochum, and the University Medical Centre in Freiburg, as well as technology developers (e.g. Micromed, Italy). We also have close collaborations with engineers in other sectors, including the oil & gas sector (e.g. BP).

Our most regular collaborators in the development of impact are academic researchers with whom we undertake research, and who form a network that connects our research to non-academic users. An example is **Romano**'s total award (£367,423) and engagement with the biotechnology company *Ingenza* (www.ingenza.com), which resulted from collaboration with Ian Stansfield from the Institute of Medical Sciences (IMS) in Aberdeen on applications of mathematical modelling to protein synthesis.. This resulted in commercial impact through minimising the number of experiments needed in the design phase of synthesized proteins, hence reducing Ingenza's production costs. We also actively explore new collaborations by taking part in cross-disciplinary meetings, such as a recent MRC sandpit on immunology, and an EPSRC sandpit on neurodegeneration scoping; and by participating in conferences and workshops in medical sciences and biology in order to identify potential applications of our research. This reflects our approach that for *model-based data analysis* and *data-based modelling*, it is essential that from the outset research is geared towards end-users. An example is **Romano**'s collaboration with the Groenemeyer Institute for Microtherapy (Case Study 3), which began as a result of **Kurth**'s

participation in a conference in 2006 in which researchers from Groenemeyer Institute presented a statistical challenge they were confronted by in their investigations of non-invasive pre-natal diagnostic methods. The solution to their problem, as phrased in terms of dynamical systems, resulted in the "twin surrogates" method. This example shows several facets of our approach, including our agility and flexibility in identifying and responding to new opportunities, and to maximise the relevance of our research to our stakeholders by actively involving end-users in the design, execution and interpretation of our research. It also demonstrates the nature of the relationship between mathematical research and impact: the mathematical challenges facing end users themselves generate new research projects. A further example of this approach is collaboration with BP, detailed in section (c), which began as a result of participation in a workshop organised by the National Subsea Research Institute (NSRI), an industry-led research partnership looking to develop research breakthroughs on behalf of the subsea industry.

In practical terms, we achieve impact by developing software packages in which we implement algorithms derived from our research. We provide access to the results by making the software available to the wider end user community, including both academic researchers in other disciplines, and non-academic users. Each of our submitted Impact Case Studies involves the compilation of software packages which are now either available to scientists as open source software, or are part of commercial products.

The impact of our research findings for medical, engineering and other challenges goes beyond the problems they are designed to solve, also shaping future research in other disciplines. For example, **Schelter**'s research (Case Study 1) resulted in his participation in the Advisory Board for a series of international workshops on epilepsy, through which the standards and specifications of an international database for epilepsy research were established, partly based on **Schelter**'s research and contribution. The key meetings took place in Kansas (2009) and Dresden (2011).

Facilities and Resources. To support the derivation of impact from these collaborations, we have invested in our own dedicated super computer facility to develop and implement our *nonlinear time series analysis* algorithms. This includes a UNIX-based High Performance Computer Cluster with 554 cores, dedicated and suitable for large-scale data-analysis and modelling.

Supporting and rewarding impact. To ensure academic staff are best placed to address the challenges of impact from research, the Unit is supported by the University's Public Engagement with Research Unit (PERU) funded through an RCUK Catalyst grant, which offers training to staff and students in a variety of public and stakeholder engagement activities. The generation of Impact is also encouraged and rewarded by the University through the Principal's Prize for Public Engagement (personal award).

c. Strategy and plans

Our research over the past 5 years has concentrated on building strong interdisciplinary links with researchers and practitioners in the fields of engineering, medicine and life sciences (especially systems biology). These established connections are a strategic asset, and we will continue to maintain our strong interface with them. For example, **Schelter** has just signed a contract with TauRx, Aberdeen, for a dementia-targeted project worth £788K to IPAM. We will also aim to expand the applications of our research to a number of different sectors, such as engineering, economics, logistics and climate studies. For example, **Baptista** currently holds an EPSRC grant (£500K) to analyse the performance of power-grids and transport networks, and **Kurths** is a senior member of the Potsdam Institute for Climate Impact Research in Germany. We will continue our close dialogue with potential end users of research into complex systems and dynamical networks to develop new models and techniques largely inspired by, and partly in response to, external demand. We plan to ensure our research responds to emerging priorities in other disciplines, and that the results of our research meet the objectives of end-users, responding to important gaps in current knowledge. An example is on-going research at IPAM dealing with the challenges of using chaotic dynamics theory applied to wireless communication systems. **Baptista** and **Grebogi**, with help from the University's legal team, are finalising a patent application of a prototype modem being developed with the objective to improve mobile and through-water wireless data transmission. Expected applications of this research will be the enhancement of the resolution of GPS vehicle-localisation in metropolitan areas, and the extension of the current short-distance/low data-rate transmission through water, to broader bandwidth transmission over considerably longer distances for applications with the subsea sector (http://phys.org/news/2013-05-chaos-wireless.html). This research has already attracted interest from a number of companies, and

emerged from direct conversations with the trade association Subsea UK, and oil & gas engineering managers who indicated this as a key enabling technology for autonomous operation of subsea assets.

These applications in the engineering sector will enable the development of impact alongside medical sciences. We are also engaged with the oil & gas sector to solve two fundamental technical challenges: (i) to monitor and improve the reliability and integrity of installed systems to minimise technical downtime and lost production, and (ii) to maximise the efficiency of operations and extend the life of installed systems. Based on fundamental research, undertaken in collaboration with the Rutherford Appleton Laboratory, we are developing a cold atom quantum sensor that potentially will significantly improve resolution for fault-detection, and will also allow engineers to inspect pipelines and umbilicals non-intrusively, and without interrupting production. This could potentially yield significant savings in repair and maintenance time of up to several tens of millions of pounds per year in the North Sea alone.

In terms of staffing, we have been careful to recruit specific, complementary research expertise in dynamical systems, to maximise our ability to respond to challenges emerging in these fields. As an example, once our track record in projects from the life sciences was established, we identified an important gap in our expertise in non-equilibrium statistical mechanics, important to address problems on the discipline boundaries with biology. For this purpose **Politi** was appointed in 2011, followed by **Ginelli**, **Perez-Reche** and **Henkes** in 2012-2013. **Baptista**, whose expertise is networks and nonlinear communication, was appointed in 2009. **Schelter**, whose expertise and competence is data-based modelling, was already key in the development of Case Studies 1 and 2 as an Honorary Fellow in IPAM, and became a permanent member of academic staff in 2012. Each of these staff members has already either delivered or developed impact through their research. We will ensure the continued professional development of postgraduate students and early career staff via staff training and development programmes to improve understanding of end-user networks, and provide them with the skills to build networks and relationships with external stakeholders. We will continue to disseminate results from individual work by means of workshops, organised externally and internally, that promote academia-industry engagements.

d. Relationship to case studies

The *Brainatics* case study (Case Study 1) exemplifies how our research has led to specific economic impact, as well as impact on practitioners and professional services, through the development of algorithms, and a database, which have enabled the development of a new device to monitor and potentially predict epileptic events. **Schelter**'s research has led to the creation of the world's largest epilepsy database, and thus also influences the development of underlying research in the medical discipline. This demonstrates our close interaction with research partners in medicine, and the close relationships we maintain with technology developers through the engagement with Micromed

The *Dementia* case study (Case Study 2) demonstrates how our academic engagement with medical researchers in Aberdeen facilitated contact with professional bodies, allowing the results of mathematical research to inform ongoing international collaborations on dementia. Algorithms developed by IPAM were used to develop software to allow new techniques to analyse brain network conditions, which are presently suspected by medical researchers to constitute early signs of dementia. The algorithms have also been applied to research in Parkinson's disease, and various other cognitive deficits. The resulting software has helped to inform not only medical research programmes at the European level, but has also been made available to medical practitioners across Europe by the Netherlands-based company BrainMarker, also contributing commercial impact to that company.

The *Mother-Foetus* case study (Case Study 3) demonstrates our agile approach to new opportunities, and the resulting adaptation of our research priorities. The development of new mathematical tools using time-series analysis was inspired by the medical need to measure and establish the coordination of pre-natal heart rhythms between mother and foetus. This has facilitated a new study investigating non-invasive methods for the early detection of foetal pathological conditions. It also demonstrates the close connections with our end-users the Groenemeyer Institute of Microtherapy, a private medical practice and research organisation, who run medical research programmes into foetal pathology and foetal arrhythmia that have been directly informed by the results of mathematical research at the University of Aberdeen.