Institution: University of Nottingham

Unit of Assessment: UOA 10 – Mathematical Sciences

a. Context. The research of the School of Mathematical Sciences at The University of Nottingham has impact in diverse areas that require the use of mathematical-science-research-dependent tools and techniques, ranging from engineering to medicine and including via a wide variety of industries. The School's impact has been facilitated by reorganising into seven research groups: Algebra and Analysis, Industrial and Applied Mathematics, Mathematical Medicine and Biology, Mathematical Physics, Number Theory and Geometry, Scientific Computation, and Statistics and Probability. This structure has proved effective in promoting innovative new research directions and facilitating intradisciplinary activity, in turn aiding external engagement and expanding impact.

The School's case studies are indicative of the wide range of activity undertaken, crossing disciplinary boundaries and spanning multiple industrial sectors. Our work has impacted on the economy (e.g. in aerospace - Pratt and Whitney in CS2 and Rolls-Royce in CS6), policy (e.g. in health and quality of life - policy assessment and cost-effectiveness analysis of MRSA control measures in CS1), the environment (e.g. in climate science - work used by the Met Office in CS5) and society (e.g. in outreach - 'Meet the Mathematicians' in CS1). The main beneficiaries are industry (via economic gains and trained employees), government (via policy advice), clinicians (via diagnostic and prognostic tools and targetted therapeutics) and the general public (via quality of life, health, understanding).

b. Approach to impact. For many years, the School has strongly encouraged interdisciplinary working, recognising the value not just of expanding academic exposure but also of connecting to end users through disciplines typically closer to applications. This has driven a number of very successful, long-lasting collaborations such as that with the Faculty of Engineering that led to the Rolls-Royce University Technology Centre (UTC) in 1998 (see CS6), and the establishment in the same year of the multidisciplinary Centre for Mathematical Medicine and Biology (CMMB), now including researchers from e.g. Life Sciences, Medicine, Engineering, and Veterinary Medicine and Science (see CS1). These relationships have led to collaborative activity that would have been impossible without the support that the School and University, as well as mechanisms such as EPSRC Bridging-the-Gaps funding (coI Cliffe), have provided. Drawing on this established approach, plans have been implemented to engage further with end users in industry and clinical settings. The appointment in 2008 of a Research Facilitator within the School has assisted staff in making these links and in embedding knowledge exchange (KE) within research activity. Success with industrial engagement schemes such as EPSRC Knowledge Transfer Secondments (KTS) and shorter Knowledge Transfer Partnerships (sKTP) (e.g. with Network Rail, Unilever) followed, building on our established successes with CASE awards (11 in the last ten years with e.g. Element Six, Health and Safety Laboratory, Pfizer, Serco/AMEC and Unilever).

Identifying and developing pathways to impact: The School regularly undertakes surveys (through desk research and interviews) to identify research activity showing the greatest potential for impact - this approach contributed to the current Research Group structure. Investment cases are considered by the School Research Board (meeting five times p.a.) and the most appropriate package of support is devised, e.g. sabbatical or buy-out time, underwriting of workshops or other events aimed at bringing end users into the School, authorised applications to KE funding schemes such as the EPSRC Impact Acceleration Account, the University's HERMES Fellowships for Business Engagement (tinyurl.com/kjtshm9) or competitions such as KTP and CASE studentships. Our case study in Dynamical Energy Analysis (CS3) exemplifies this approach. The value of the work led by Tanner was recognised at an early stage and interaction with the main industrial partner inuTech was encouraged. An 8-month KTS with Jaguar Land Rover in 2012 funded a proof-of-concept study implementing the methods on a large scale. The School then awarded Tanner a 16-month sabbatical to work with inuTech, which extended connections with other companies and led to an EC-funded project in 2013 involving Jaguar Land Rover, who were looking to continue investment in the methods following the KTS, and inuTech, who were seeking to extend their client base using the success of the developed software tool.

Establishing and maximising partnerships with industry: There has been a drive within the School to pursue long-lasting relationships with industry, building on our successes such as through CASE awards and internships. This led to e.g. the award of an EC-funded Marie Curie Initial Training Network (ITN) in 2012 to Coombes, which is training 20 researchers over four years and includes internships and tailored training with 12 European companies (see CS1). The EC project with Jaguar Land Rover (Tanner) resulted from an earlier project (2009-2012) that produced a software tool for the industrial partner inuTech, which is now being developed with input from service providers such as Germanischer Lloyd, as well as from Jaguar Land Rover (see CS3). Activities with Unilever (e.g. sKTP, CASE, Study Groups) contributed to the recently (2013) formed Framework Partnership with the University (tinyurl.com/d8dypj8, and CS1).

Staff are encouraged to develop relationships with industry through consultancy – a valuable entry point for business, e.g. Cliffe and Houston's work with Element Six led to a CASE award in 2012. Several of our PGRs have been recruited to such end-user partners, including AMEC, the Health and Safety Laboratory and Rolls-Royce.

Modifying the long-running model developed by Oxford, the School established innovative annual Study Groups with end users in Mathematics in Medicine (from 2000, with follow-up meetings including hostings by industry, e.g. Syngenta in 2011), Plant Sciences (from 2007) and the Virtual Physiological Human (from 2009). All arose from CMMB activity and the desire to encourage interdisciplinary working and end-user engagement. Attendees have included Pfizer, Syngenta, Unilever and clinicians, cf. CS1. The success of this format has led to related Study Group activity in Canada and the US, as well as a recent event (2013) coordinated by NC3Rs. Further similar activity includes hosting a European Study Group with Industry in 2007 that involved e.g. Schlumberger and Unilever, both of which generated further collaboration.

Engagement through networks (see also REF5e)**:** Staff have led international networks such as the Mathematical Neuroscience Network (mathneuronet.org.uk) and the Quantum Geometry and Quantum Gravity network (tinyurl.com/m35maaw). Other illustrative international activities include a Royal Society exchange with the University of Queensland (Fuentes), a BBSRC partnership with the Mathematical Bioscience Institute in Ohio (Owen) and participation in recent research programmes at the US Simons Foundation (Bogomolov). These initiatives to extend our reach have produced new collaborations with experimentalists and application-facing academics and are expected to lead to wider impact through the formation of consortia for new ITNs, IAPPs (Industry-Academia Partnerships and Pathways) and similar schemes involving industry participation.

At a national level, Billingham and King are directly involved in the Industrial Mathematics Knowledge Transfer Network (KTN) as Scientific Committee members (Dryden is an ex-member) and have encouraged involvement in the sKTP programme. We have received five sKTP awards, including with Airbus, Russell Group Limited and Unilever, more than any other UK mathematics department; a Russell report (tinyurl.com/mpabt34) highlights great benefits: *"For a number of years, Russell have had the ambition to provide analytical techniques to (re)insurers which would, for a given risk appetite, balance risk and reward. This EPSRC-funded project with Nottingham University has enabled Russell to finally realise its ambition".*

Engaging with schools and the wider public: The School employs dedicated staff who liaise with local schools (and participates in the Centre for Plant Integrative Biology's work with primary schools), as well as a marketing co-ordinator who collates and disseminates School-related news stories. Staff are involved in the annual MayFest community day (2011 to present), Open Days and other events based on their research – an example is 'Meet the Mathematicians' in 2009 (see also CS1) where the associated YouTube video (tinyurl.com/db2q72) has attracted more than 77,000 visitors with 97% positive feedback. A School drive to encourage staff to publish in highly visible and prestigious multidisciplinary journals, such as Nature (Farcot, accepted October 2013) and PNAS (Coombes, King, Owen, Thul), is also paying dividends through media coverage. Notable examples include: 'Using math to feed the world' (Owen, King) and 'The mathematics of a heart beat could save lives' (Thul), which were covered in numerous science blogs and other sites; Numberphile (http://www.numberphile.com/), a collection of online videos encouraging public

interest in properties of numbers; and high-profile articles in e.g. New Scientist 'Quantum thermometer could measure coldest thing ever', 'Space oddity: putting quantum weirdness into orbit' (Fuentes) and the Economist 'How to build a multiverse' (Weinfurtner), all in 2013. These initiatives increase our reach to groups unaware of results published in standard mathematical journals, and increase general understanding of the research. Evidence of the success of this approach is exemplified by the hospital infections work in CS1 that was picked up by the Health Protection Agency and contributed to discussions around national MRSA screening policy.

c. Strategy and plans. The School's KE Framework aligns with that of the University, recognising KE as a core activity underpinning research and teaching. It builds on existing, successful KE mechanisms being utilised across the University and promotes new priorities for action to increase effective external engagement, income generation and impact.

Enabling: The staff workload model will continue to reward those undertaking industrial or public engagement activities and thus promote impact-related activity. Similarly, the School sabbatical scheme will sustain an environment for the enhancement of KE activities, as will the promotion of other internal and external buy-out opportunities. The School Research Board will act on new opportunities for growth aligning to national and international priority areas, e.g. Mathematical Medicine and Biology links to global issues on food security and drug development and Industrial and Applied Mathematics links to the aerospace and transport sectors, sectors in which there is current substantial investment. When there is a need, measures will be taken to strengthen any shortfall in personnel or expertise, e.g. discussions around strengthening Scientific Computation resulted in the appointments of Tretyakov in 2012, van der Zee and Iglesias in 2013 and Hubbard from 2014, and discussions to expand expertise in applied analysis and partial differential equations (to provide links between the Algebra and Analysis, Industrial and Applied Mathematics and Scientific Computation groups) resulted in the appointments of Zhang in 2012 and van Gennip and Kurzke in 2013. The School is currently building activity in Uncertainty Quantification, expanding its current expertise (e.g. Cliffe, Dryden, Tretyakov, Wilkinson) and forming a Centre of Excellence. Its potential has been independently confirmed by Mark Girolami (UCL) on a recent advisory visit, by interest from companies such as Pratt and Whitney (CS2) and Unilever and by an approach from our colleagues in Engineering to support research in stochastic and computational electromagnetic modelling. It is expected that this venture will allow considerable impact (such as economic via efficiency savings) to develop through these and other industrial links.

Engaging: A key strength of the School has for many years been the exceptional extent of its research with other disciplines. Evidence of the success of this approach is abundant, for example through grant income and increased interaction with end users. The development of novel mathematical techniques for use in new applications will continue to be a strong driver of School research activity. We will continue to promote (through regular liaison with research development staff, coordinated promotion and joint discussions) interaction with end users of academic research through collaborators in e.g. the Engineering and Medical Faculties. Public engagement is a further important part of the School's activity and most recently we have contributed to events such as Brain Awareness week (March 2013) and Public Lectures such as that by Bill Unruh (on black holes, June 2013). Future plans for the School in this area include the creation of a 'Bright Club' (brightclub.wordpress.com) at Nottingham, aided by our teaching support and outreach staff, and use of new schemes such as the RCUK-funded Nottingham Catalyst (tinyurl.com/l4p4bq9) and 'University of Nottingham on Tour' (tinyurl.com/pd32y8g). Social media are becoming of increasing importance, and have been successfully employed in e.g. recruitment of researchers and (in the above ITN) professional and social networking. The School will encourage staff and research students to promote their interests further using social media and through mechanisms such as the University technology demonstrator (tinyurl.com/oryu7et) and time capsule (tinyurl.com/qbucywk).

Delivering: The School is committed to expanding its links to industrial partners, building on the success of projects co-funded by e.g. the EC, University and Research Councils. The School is taking action to promote the development of further long-term partnerships with companies. The Research Facilitator, whose post has recently been made permanent, is working with the University Corporate Partnerships Team to enhance and deepen existing relationships with Experian, Network Rail and Unilever, in particular. The School sabbatical scheme has been

revised to allow better planning when potential for impact has been identified. This has proved to be successful (see CS3) and the School intends to expand on this, having already approved sabbaticals in 2013/14 for Graham (to facilitate opportunities to engage with industry in carbon capture and storage and polymer dynamics), Wilkinson (to work on climate reconstruction using proxy data) and Coombes (to develop mathematical models of pain). The School continues to encourage staff to make use of new funding mechanisms such as the EPSRC Impact Acceleration Account and the University's HERMES fellowships mentioned in **b**, as well as established sources such as KTP and CASE; Study Groups with, and seminars by, industry speakers will continue as excellent first steps toward collaboration.

Reaching Globally: As noted in **b,** the School has been actively seeking to expand its reach by creating international links through research networks and visiting-researcher programmes. The School plans to increase activity in this area, with particular attention being paid to schemes such as ITN and IAPP, and to pursue routes to commercialisation vigorously. Successes have already been achieved (see CS1, CS3) with these, and further collaborations built this way will enhance knowledge transfer into the UK; in particular the School is targetting other world-leading institutions to expand its reach and build potential consortia. Further exploitation will be made of the University's campuses in Asia (China, Malaysia) – hitherto activity has been focussed on teaching but, now that the campuses are well established, joint research activity and KE are viable. This will allow us to extend our profile and influence in Asia and open access to funding streams there.

d. Relationship to case studies. We have selected six case studies that together provide a broad picture of impact-related activity within the School, encompassing a variety of industrial sectors, including aerospace, healthcare, ICT, pharmaceuticals and transport.

CS1: Advancing the use of mathematics and statistics to address medical and biological problems. Impact: change in R&D practices, influence on government policy discussion, change in perceptions of end users/public. Mathematics and biomedicine are not the most obvious pairing to a non-expert: CMMB initiatives such as the Study Groups, with support from the School and University, have been instrumental in increasing the profile and acceptance of the research.

CS2: Enhancing competitive advantage at Pratt & Whitney using Design for Variation. Impact: efficiency gains for Pratt and Whitney, change in R&D practices. The impact stems from work in the 1990s, illustrating that industrially-relevant research has been a feature at Nottingham for many years. It also informed current plans to increase our visibility in Uncertainty Quantification.

CS3: Enhancing vibro-acoustic modelling of built-up structures for industrial partners in the transport sector. Impact: efficiency gains, reduction in noise pollution, improvement in comfort. The accelerated impact here was realised by making effective use of internal support including a KTS written with the Research Facilitator and sabbatical leave for Tanner to further industrial links.

CS4: Improved movement and fingerprint analysis using statistical shape analysis in computer vision. Impact: efficiency gains, change in R&D practices. Impact was supported through a 2012 Royal Society Wolfson Research Merit Award for Dryden to explore further the applications of his work in object data analysis to medical imaging and molecular structure.

CS5: Incorporating expert knowledge in complex industrial and policy applications. Impact: efficiency gains for a wide range of users, policy influence, environmental effects. Part of the underlying research was supported by a University-funded studentship, without which the impact may not have been of the same level and range.

CS6: Supporting Rolls-Royce in new aero-engine transmission designs Impact: efficiency gains and competitive edge for Rolls-Royce, environmental gains of reduced noise and fuel usage, enabled through continuous and effective School and University support for over 15 years. This support was instrumental in securing the award by Rolls-Royce of a UTC in 1998, in the encouragement of Maths-Engineering connections, e.g. establishment of the Spencer Institute in 2007, and in supporting regular interaction with Rolls-Royce, e.g. seed funding of a Chair (Cliffe).