Institution: Imperial College London

Unit of Assessment: 10 Mathematical Sciences

a. Context

We work to ensure that our research in Mathematics comprises a healthy mix of fundamental and applied research, ranging from the very "pure" to the very "applied", recognising that, as "the Queen of Sciences", advances in Mathematics and Statistics readily translate into applications. Modern technology that drives everyday life would be unthinkable without advanced mathematics and, reflecting this, our impact is very broad. Our research groups cover all areas of Pure Mathematics, Applied Mathematics and Statistics and all contribute to impact to some degree. The main non-academic users of our research fall broadly in the following categories:

Financial sector. Banks, hedge funds, insurance, and investment companies require advanced mathematical tools, often using stochastic analysis, and our expertise from Mathematical Finance and Statistics groupings is in demand from many financial institutions, namely investment banks, commercial banks, central banks, regulators, asset managers, government bodies, and legislators [case studies C1,C2,C3]. We have part-time PhD students working in Citigroup, Nomura, Credit Suisse, Mediobanca and HSBC, visiting Professors from the financial sector and our staff have leading roles in Natixis (Cont) and Capco (Brigo) and advise National Banks and regulators. Our interests range from derivatives and trading strategies [C1] through to counterparty credit risk, funding and liquidity risk, and identifying systemic risk associated with the aftermath of the credit crunch crisis. A distinct strand of our Statistics research is in retail banking [C3] and credit scoring [C2]; this too is in strong demand and has had high impact again through strong industrial linkage, to Winton Capital, Scorex, Experian and RBS amongst others. Related work has impact through long-standing financial security and risk issues [C2,C3] with examples being: British Credit Trust, Capital One and GMAC in evaluating scorecards; HBOS in pattern discovery for retail banking data; Goldman Sachs in fraud detection.

Health sector. Our research is used to effect in Public Health aiding in the analysis of clinical and epidemiological studies and in NHS performance monitoring. Our Biostatistics group provided the mathematical and computational underpinning of the software package WINBUGS widely used in Bayesian analysis of numerous problems, including clinical trials and public health decision making [C4]. We engage actively with Government through the Care Quality Commission and our monthly mortality alerts were major triggers in the investigation of the Mid-Staffordshire NHS Trust and have influenced NHS policy on weekend admissions and junior doctor working arrangements [C5].

Industry. The Department is fortunate to be alongside world-class Engineering and Natural Sciences Departments and long-term cross-Departmental collaborations have led to sophisticated Mathematics impacting directly in Aerospace (Airbus, Bombardier) [C7], computer hardware (IBM) [C8], defence (BAE systems) [C11], energy (EDF), biotechnology (Syngenta), ultrasonic inspection (Rolls- Royce, Serco) [C9] and nuclear industries (CEA) [C9] amongst others. A particular strength of these strong linkages is the speed at which theoretical advances from Mathematics feed both into Engineering and into tools required by the end user [C7,C9,C11].

National Security. Our statistical expertise is actively procured by a number of UK government bodies and institutions, including the MoD (DSTL), GCHQ, and in the USA by the Los Alamos National Laboratory. The analysis of large data sets is topical and important, and we have staff seconded to work on national security issues such as security applications of data streaming and network data mining [C11]. This expertise is now feeding into data analysis more broadly.

Education. We actively engage with the Department for Education (DfE) by providing expert advice that informs policy and good practice, i.e. during the National Curriculum reform. We take a leading role in the Further Mathematics training of pupils and in the continuing professional development of teachers. This complements our public engagement activities that engage a diverse range of audiences through public lectures, exhibits and media outreach informing and educating the public of the purpose, and benefits, of Mathematical research.

b. Approach to impact

Imperial College has the application of its work to industry, commerce and healthcare as central to its mission. Knowledge transfer and commercial exploitation of research are integral to our activities and supported centrally through Imperial Consultants, Imperial Innovations Group PLC and the start-up Incubator. The Faculty of Natural Sciences, within which Mathematics sits,

provides funding with a strong interdisciplinary incentive under its Collaboration *Kick-start*, *Imperial strategic fund* and Creativity Lab schemes (£115K of Mathematics funding to, for instance, establish a college centre in Computational Methods in Science and Engineering (CMSE), and support the Visitor Programme of the UK centre for Laminar Flow Control (LFC-UK), which is based in the Department). Centrally, impact is supported through the EPSRC Impact Acceleration account and other locally run EPSRC–funded schemes: *Developing Leaders*, *International research collaborations, Kickstart, Knowledge Transfer Secondments (KTS) grants, PhD plus, Pathways to Impact, Efficiency and effectiveness strategic funds* and *Bridging the Gaps.* 20 grants totalling £368K have been awarded to Mathematics since 2011; these cover a wide range of activities producing impact, for instance, modelling genetic diseases, responding to the emergent antibiotic resistance of disease, and for software for anomaly detection in networks.

Our research is aimed at solving outstanding challenges in mathematics, mainly driven by the academic community in mathematics and related scientific and engineering disciplines. Historically, our pathways to non-academic impact involved, in the first instance, collaborations with other Departments orientated toward implementation, before results reached end-users. This approach remains successful, but is increasingly augmented by direct interaction with the end-users.

Research quality is the key factor in enabling distinctive impact. Quality is deeply rooted in our hiring policy (see also REF5) and our research environment, overseen by the Department's Research Committee. The duration and breadth of our impact from high quality academic research lasts well beyond the 20-year period set by REF and often becomes the generic methodology in a field, e.g. the Cash-Karp ODE solvers and Davis's piecewise stochastic dynamics amongst much else. Even in areas where there are long timelines to impact, such as Pure Mathematics, our staff act in consultant roles where they have impact upon national security issues, and our PhDs/RAs progress to roles, e.g. in GCHQ. Our location in the centre of London, with its excellent transport links to the rest of the UK, Europe and globally, our proximity to the City of London [C1,C2,C3,C11] initiatives such as the Francis Crick Institute and Imperial West (see REF5) and recently awarded Centres for Doctoral training (CDTs) are all opportunities that inform our strategic vision toward impact. Our current approach to impact strategy has the following components:

Consultancy: The Department exercises maximum flexibility to enable the engagement of academic staff in consultancies, often mediated by Imperial College's *Imperial Consultants* (ICON), and this has often developed into impact cases [C2,C7,C9,C11]. One day per week is allowed for consultancy work and this enables staff to capitalise on their specialised knowledge and expertise: Adams, as ICON Knowledge Transfer Fellow, advises staff on consultancy opportunities. Since 2007/8, ICON has brokered 30 commercial consulting projects between 15 researchers in the Mathematics Department and 21 external clients, including government bodies such as DSTL, private individuals and large organisations from various sectors (including Manufacturing, Chemicals, Property Management, Law, IT services). The total value of the projects undertaken was £412K. Examples include Craster and Skelton (MoD DSTL), Adams (BAE) [C11], and Gandy (IBM). Start-ups are also encouraged, with Anagnostopoulos as Chief Data Scientist of Mentat Innovations (www.ment.at) [C11] based within the Imperial Incubator—a hub for innovation and entrepreneurship that provides office and lab space for early-stage companies.

***Interdisciplinary collaboration and industry follow through*:** The Department strongly supports collaborations with Imperial's world-class Departments in the Faculties of Engineering, Natural Sciences and Medicine and these act to facilitate our impact into applications. Over the REF period 29% of research grants have formal collaboration with other Departments, other institutions or overseas. Our strength in Continuum and Fluid Mechanics is intimately linked with research in Engineering [C7, C9]. The expertise in Imperial's Biostatistics group in the Faculty of Medicine [C4, C5] is intimately related to the strength in Bayesian Statistics in the Mathematics Department [see also C3]. Interdisciplinary research centres with substantial Mathematics Department input at Imperial College during the assessment period include the Centre for Integrative Systems Biology (CISBIC), the Grantham Institute for Climate Change, the Imperial Centre for Inference and Cosmology, the Mathematical Sciences Institute, the UK Centre for Research in Non-Destructive Evaluation (RCNDE), LFC-UK and CMSE. In recent years, closer links have been developed with Life Sciences via the British Heart Foundation Centre of Research Excellence (renewed 2014 to 2019), two large cross-departmental BBSRC grants (Combinatorial Responses of Fungal Pathogens and Data-driven multi-level modeling of stress response in bacteria), an EPSRC Synthetic Biology multi-institutional grant, strong involvement in a €3.8M Marie-Curie Training

network (joint with Syngenta), and three Doctoral training centres (EPSRC, BBSRC and Cancer Research UK funded). Examples of follow-through abound, an exemplar being the LFC-UK [C7] where the research and industry centre that has been developed, initially with EADS/Airbus and EPSRC funding of £5M, has now secured additional funding from Bombardier and is influencing wing design to be flight tested in 2015. Embedded long-term research, alongside Mechanical Engineering through RCNDE, on elastic waves and non-destructive testing, means that Mathematical advances [C9] are fed directly into software (DISPERSE) licensed by Imperial Consultants. RCNDE involves substantial industrial involvement, so Mathematical research follows through into Rolls-Royce and, in 2011, to an invitation to join SIMPOSIUM (an EU/Industry €5.9M project administered by the French Nuclear Authority, CEA). This all acts as an efficient pipeline through which Mathematics rapidly reaches the end-user and whereby real industry problems are rapidly fed back into academia. CASE PhD studentships have been an effective mechanism in enabling these links to grow with sponsors such as MoD (DSTL), AWE and Airbus EADS.

Enabling workshops: To create relationships and provide Mathematical input directly into industry and applied science the Department runs regular workshops with a distinctive industry facing focus. The most recent examples are *Model Risk in Credit Scoring (2012)*, *Critical transitions in complex systems* (2012), *The role of streaks in transition and turbulent shear flows (2012), Big data mining* (2013), *Conformal geometry in mapping, imaging and sensing* (2013), *Decision making in nature (2013*), *Large deviations theory* (2013), and two *Laminar Flow Control Industry/Academia Workshops (2012, 2013)*. This interaction rapidly creates benefits, for instance, the Critical Transitions workshop led almost immediately to an EU FP7 ITN PhD training network application involving British Telecom. Members of staff also take leading roles in outside events, like the EPSRC *Maths of Life sandpit* (Buck).

Engaging with Education: Imperial Mathematics has been strongly engaged with schools and Mathematics Education for well over 20 years. A principal teaching fellow (Ramsden) coordinates and implements this activity. He heads the METRIC Project, providing online resources for A-level and for the transition to degree-level Mathematics, coordinates our contribution to the Further Mathematics Support Programme, has served on the Qualifications and Curriculum Authority A-level Mathematics Working Group, and delivers a Summer School funded by the Sutton Trust. We have shaped policy at the Department for Education (DfE), where McCoy was a mathematics expert at all levels from Key Stage (KS)2 to KS4, part of a KS2/3 continuing professional development group and on the expert panel selecting mathematics specialist initial teacher training programmes. The DfE also approached us, in 2012, to develop a course of Continuing Professional Development for A-level Mathematics teachers in the form of a summer school and a coordinated year-long training program to enhance the capability and skills of 40 existing teachers per year; the first cohort started in Summer 2013.

Finance Industry relations: Our consumer credit risk grouping has had long-standing interactions with industry, to the extent that in 2012 it received the major *Credit Collections and Risk* industry award for its “Contributions to the Industry”. This is further evidenced by, for instance, a lectureship funded by Scorex Ltd since 2009 to support the teaching of a credit scoring module and to support research in retail finance - the industry workshop *Model Risk in Credit Scoring,* and joint work with Fitch Ratings, RBS, Scorex and Business Schools on modeling bank ratings and retail credit risk all follow-through from this. A monthly *London Quantitative Finance Seminar* sponsored by BNP Paribas, SEBA International and Palgrave Macmillan has become a key interface between academic research and the finance industry and it regularly attracts audiences of over 200. Our Mathematical Finance group hosts visiting professors from the Banca IMI (Pallavicini), Bank of America (Lipton), Apollo Asset Management (Martin) and the Bank of England (Tasche) and, currently, 40% of the PhD students in Mathematical Finance are industry-funded. Strategic hires of Chairs in Mathematical Finance have been made with an eye to creating strong linkage to the City of London: Brigo was Global Head of Quantitative Analysis for Fitch Solutions and Cont acts as consultant to HSBC, the Federal Reserve, Bank of England and the Basel Committee. Follow-through from this is that joint research projects in quantitative finance are under way with Citigroup, CreditSuisse, DeutscheBank, Shell, Bank of England, Bank for International Settlement, the Central Bank of Norway and Mediobanca. Research has been cited as evidence (Cont) in recent high-profile international lawsuits regarding the rating and pricing of derivative securities and has led to the creation of a European exit probability index, CEPIX (Brigo). This activity has recently led to a leading hedge fund, Capital Fund Management, collaborating with us to establish a joint

institute for high-visibility research in Quantitative Finance and Risk Management.

Public engagement: The Department actively encourages staff participation in public engagement and outreach activities with a recently appointed coordinator (Coates) to oversee this increasing activity. Our staff regularly give LMS Popular Lectures and talks at "science cafe"-style events, for example, Buck and Ramsden have an ongoing EPSRC funded project (Maths in Medicine) with the Science Museum's Dana Centre. We contributed to the Royal Society Summer Science Exhibition in 2009 (Lamb) and again in 2013 (Mortlock – a joint appointment with Physics), we give monthly Royal Institution Masterclasses (McCoy) and have a Mathematics podcast (Adams). Our artist in residence, Anderson, funded by the Leverhulme Trust and EPSRC, and the associated Fanosearch project, has attracted substantial media attention (New Scientist, Cosmos and Physics World) and featured at the 2012 Imperial Festival to which the Department always contributes. Media outreach such as the popular Guardian Olympics alternative medals table, generated by Statisticians from Imperial, and media coverage of breakthroughs such as those in complex analysis by Crowdy or in snowflake simulation by Barrett and Nurnberg are also notable.

Public sector roles: The Department exercises maximum flexibility, by providing leave, to allow academic staff to accept public sector roles that provide policy impact. For instance, Hand was supported to serve as a member of the Office for National Statistics (ONS) Methodology Advisory Committee (2001-9), the UK Statistics Authority Committee on Official Statistics (2010-), UEA Climatic Research Unit Scientific Assessment Panel (2010), UK Strategic Forum for the Social Sciences (2010-2012), and the ONS Measuring National Wellbeing Technical Advisory Group (2011-). These roles have had direct impact upon public policy and informing government; for instance, the panel assessment, chaired by Lord Oxburgh, of the UEA Climatic Research Unit email controversy, “Climategate”, has informed public discussion over the use of climate change science data. The financial crisis has highlighted regulation and management of risk as being particularly important and Cont acts as consultant to the UK Government Office of Science, the New York Federal Reserve and Basel Committee for International Banking Reform.

Staffing policy: Success in achieving impact is a recognised and important contribution in decisions on staff hiring, release from probation and staff promotion. Contribution to impact is reviewed in annual staff appraisals by the Head of Department, which also involve discussion of how the Department can facilitate and support staff members to develop impact from their research. The creation and development of strong external and internal collaborations is valuable and mechanisms which the Department has put in place to support staff include flexible and responsive funding for travel to external organisations to participate in collaborative work and the facilitation of secondments through sabbaticals and the appointment of teaching fellows to cover education responsibilities. Examples of successes achieved through these mechanisms include: Hand to Winton Capital Management (2010-2011); Adams (2011-2014) and Heard (2013) to the Heilbronn Institute to work on national security issues; Stark (2007-2009) to take up appointment as Director of Centre for Integrative Systems Biology at Imperial College (CISBIC); and Heard and his PhD student (2011,2012) to Los Alamos [C11] to work on National Security.

c. Strategy and plans

The Mathematics Department has an impact strategy that involves the continuation of policies that have proven to be effective catalysers for impact, as discussed above, but at the same time we are evolving new initiatives that respond to opportunity, such as new CDTs and the associated industry partners. The overall objective is to develop substantial research projects with impact potential. Our approach has been centred on research quality and reaching out either through interdisciplinary collaborations or directly to end-users. The current strategy adds to this through the identification of opportunities and needs at an early stage, to provide small scale pump-prime and seed funding. Areas of research growth within the Department namely Financial Mathematics, Data Analysis and Biomathematics, have clear potential for future impact and will be encouraged and supported in this regard. We are developing our impact strategy as follows:

Industry partners and advisory boards: We actively participate in discussions at College level with industry partners (e.g. Procter and Gamble) and private funding bodies (e.g. Cancer Research UK) and we seek to expand this direct involvement by taking advantage of key Strategic Partnerships negotiated at College level. In areas where we already have substantial direct links, Mathematical Finance and Consumer Credit Risk, we will constitute Industry Advisory Boards to ensure that our research effort is channelled into the most beneficial avenues.

Sabbaticals and secondments: Sabbatical leave is considered annually by the Management

Committee and requires a justification (such as collaboration or research funding etc) and impact is also considered as a factor. It is recognised that this has been a strong factor in delivering impact in cases [C1,C2,C6,C7,C11]. Impact has already been used to support applications for sabbaticals (as above), or unpaid leave to enable secondments, that are primarily aimed at impact generation, and such applications will continue to be encouraged.

Software: We have identified the development of software and prototypes of ideas as a bottleneck for impact, we are therefore creating infrastructure with backing from Imperial College's EPSRC Pathways to Impact (£380K award for an Advanced Hackspace to start in the Autumn of 2013). An allocation of support is to be made enabling staff to employ programmers on an on-demand basis.

Topical research groups developing long-term cross-departmental links: We generate impact through our relationships with world leading research in Engineering [C7,C9] and Medicine [C4,C5], which, in turn, also facilitate the development of industrial relations. Given our success with enabling workshops, we seek to expand this further. To effectively mobilize research staff to work on interdisciplinary topical themes, and make these visible and recognizable to the outside world, topical research groups have been established that form a focal point for the activity. Examples of such foci are current initiatives in Probability and Big Data, in Systems and Synthetic Biology and in Advanced Materials/Metamaterials.

d. Relationship to case studies

Our approach to impact embodies high quality fundamental science, strong collaboration with industry and with facilitating partner Departments in Engineering, Life Sciences and Medicine. This is coupled to flexible sabbatical leave and opportunities for secondments. Involvement by graduate students and RAs in impact is encouraged and sometimes, of course, in impact serendipity plays a natural role. Each impact case demonstrates and exemplifies at least one of these approaches.

C1 *A robust algorithm for the risk management of derivatives in foreign exchange markets used by financial institutions*: Initial impact created by close collaborations of Mijatovic and his PhD student with RBS. Follow-up and continuing widespread impact is consolidated by industry workshops and frequent on-site presentations at numerous financial institutions.

C2 *Statistics in retail banking: evaluating scorecards*: Collaborative industry research aided by an industry funded lectureship, focussed industry workshops, sabbatical leave and consultancy.

C3 *Applications of Bayesian methods in finance, credit scoring and target tracking:* Widespread and generic usage of fundamental science created due to the critical mass of high quality staff.

C4 *WinBUGS: Bayesian inference using Gibbs sampling.*

C5 *Improving the safety and quality of healthcare delivery using routine data*: Both [C4] and [C5] are facilitated by strong cross-departmental interactions between Public Health in Faculty of Medicine and Mathematics leading to impact in Medicine and the NHS.

C6 *Advances in methodological and algorithmic wavelet analysis used widely internationally for the analysis of time series:* This wide usage was triggered by Walden's research exposited in a highly successful book, enabled by sabbatical leave.

C7 *Theoretical and computational underpinning of laminar airfoil design:* A long-term interdisciplinary and industry collaboration augmented by targeted hires, embedded industry relations through incoming secondments and sabbatical leaves that have all facilitated impact.

C8 *A theoretical prediction leading to new technology used in every modern hard-disk drive.* Fundamental high quality science creating a research breakthrough that led to high impact.

C9 *Modelling of bulk and guided waves in the non-destructive evaluation of structures:* Research intertwined with Engineering and facilitated by extensive cross-departmental and industry funding with co-supervised PhD students, close linkage with Rolls-Royce and licensed software.

C10 *Forecasting ocean oil spill movements, facilitating oil spill clean-ups:* Long term collaboration with the US Naval Research Laboratory triggered by teaching and regular research visits.

C11 *Security applications of streaming and network data mining:* Secondment of Adams, and now of Heard too, to the Heilbronn Institute, now also creating a growing list of collaborations external to national security. Initial visits to Los Alamos, funded by the Platform grant, have aided impact.

The cases inform our strategy as: seed funding for travel/workshops with non-academic partners has been key in [C1,C2,C11], our successes with Financial Services [C1,C2,C3] motivates a coordinated approach to interaction with industry, further sabbaticals and secondments on impact grounds are to be further encouraged as these have played a pivotal role in many of our case studies [C1,C2,C6,C7,C11]. We have benefited from long-term relationships with Engineering [C7,C9] and Medicine [C4,C5], which in turn also facilitate the development of industrial relations.