Institution:	University of Manchester (UoM)
Unit of Assessment (UoA):	B10 (Mathematical Sciences)

a. Context

The principal **beneficiaries and audiences** for the UoA (covering the School of Mathematics) are

- *schools and the general public* through public engagement activity
- *industrial sectors* including engineering, mining, defence, software, pharmaceutical and medical, financial and commercial, through CASE PhD studentships, KTP & KTA positions, collaborative grants and consultancies
- *government and charitable bodies*, e.g. DSTL, British Antarctic Survey, '*Find a Better Way*' landmine charity, National Oceanography Centre, Peak District Park Authority and Rutherford Appleton Laboratory through similar collaborative mechanisms to the industrial sectors

The principal **types of impact** are

- communication of mathematics and science to the general public and schools;
  these activities are undertaken by all research groups within the UoA
- professional services, advice, consultancies and research support, including CPD;
  these activities are undertaken by all research groups within the UoA
- improved efficiency and efficacy of software;
  principally work by the numerical analysis group
- improved understanding, practice, behaviour and activity through industrial modelling, such as optimising product design, testing and construction; predictive and forecasting methods; and materials characterisation;
  sub-groups within applied maths and statistics, as well as intradisciplinary pure groups
- improved understanding and awareness in the biotechnology and health sector;
  undertaken by sub-groups in applied mathematics and statistics
- contribution to policy via national and international advisory boards and learned society activity;
  undertaken by various (senior) members of the UoA

b. Approach to impact

Since RAE2008, interdisciplinary research has had a high priority within the UoA, as has the promulgation of its research to a broad audience. During the REF period there has been a step change in outward-facing research activity, particularly in industrial mathematics, with a 15-fold increase in industrial-related income to just under £2m. The UoA sees impact-led activity as a critical element of a virtuous circle, whereby core mathematics is applied in novel ways and to new applications areas, which in turn identifies open mathematical issues that then inform new basic research.

Interactions and impact mechanisms The mechanisms employed to achieve this step change include:

i. Employing a Knowledge Transfer Fellow/ Technology Translator A core element of the UoA's approach to impact is the establishing of new industrial partnerships, and provision of support to enable them to flourish long-term. This has been facilitated by the appointment of a Technology Translator, who has been a key success (Evatt - initially funded by KTA in 2010, appointed Lecturer in Industrial Mathematics in 2012 and Director of Industrial Liaison). His introduction has led to a number of initiatives to bring staff and industrial partners together, providing a focal point and conduit for new external partners seeking mathematical expertise; supporting colleagues when applying for funding from a wide variety of sources; and initiating new avenues for interactions.

ii. Industrial study days The development of a programme of study days was directly influenced by the demand from industry to '*come with their problems*' (7 study days in the last two years from companies such as Arup, NNSP, Dstl). Typically a single company (with Technology Translator input) will present 4 or 5 problems to the staff in the UoA, who spend the day modelling these in group format. The outcomes are often new ways of addressing specific problems and there has been considerable success in obtaining follow-up funding to pursue longer-term analysis (11 MSc, PhD and PDRA projects funded to date, 2 KTPs, plus exploratory consultancy work). Study days provide an easy way for all staff to develop relationships with key industrial users and beneficiaries.

iii. Discerning funding opportunities to nurture and support intra and interdisciplinary research across all research areas of the UoA The UoA has proved flexible and opportunistic in obtaining

funding from a wide variety of sources to support research with direct impact on the non-academic community. These include

- a Royal Society Industry Fellow (from Thales UK) positioned within the School (~£200k for half-salary for 4 years plus expenses)
- over £1m (out of a total UoM pot of £8.3m) secured for Mathematics from the University's recent EPSRC Knowledge Transfer Account (KTA)
- EPSRC MAthematics PLatform Engagement Grant (MAPLE) to stimulate intra and interdisciplinary activity across the whole UoA (£526k)
- William Penney Fellowship (£312k) to promote knowledge transfer between the AWE and UoA
- EPSRC backed industry collaboration grant with Rapiscan (£497k for MIRAN)
- Thales '*SMART Hub*' funding (£150k) for initiation and *pull-through* of existing collaborations with UoM
- grants from a broad range of industrial bodies totalling just under £2m since 2008, a 15-fold increase over the RAE2008 (adjusted) period, including for example AWE (£164k); Dstl (£124k); NAG (£146k); National Grid (£143k); Federal Mogul (£75k); Kraft Foods (£47k)

The MAPLE grant has been particularly beneficial as it enables the UoA to form new internal links and thence engagement with external users. It therefore opens the possibilities for interaction between non-academics and a much wider internal group than just the traditional applied mathematicians and statisticians. In addition, its rapid-response funding mechanism for pilot projects enhances the UoA's agility when responding to opportunities arising from industry, research councils or other external parties. MAPLE also supports additional Technology Translator time, and Creativity@home workshops to enhance the groups' strengths at interdisciplinary work.

The UoA recognises the value of its staff undertaking consultancy and providing services for outside bodies, as long as it forms part of the aforementioned virtuous circle, i.e. the work should apply mathematics in innovative ways or to novel applications areas. Since 2008, the UoA has provided consultancy services to some 17 companies (including The MathWorks, We Buy Any Car, British Nuclear Fuels) many of which have led to longer-term research projects that bring overhead income to the UoA.

iv. Increasing industrial involvement in the training & research activities of MSc and PhD Students
Regarding postgraduate students, opportunities for external interaction have been increased:

- two EPSRC CASE studentships per year sponsored by industry for the last four years (bringing ~£90k per studentship)
- averaging two further PhDs per year fully funded by industry (e.g. Astra Zeneca, ARUP, Cadbury Chocolate, Federal Mogul, Fujitsu) (~£70k per year)
- internships for PhD students (10 in the last 3 years) from a wide variety of partners often via the Industrial Mathematics Knowledge Transfer Network (KTN) supported by the sKTP scheme
- new MSc Programme in Applied Mathematics (with an Industrial Mathematics focus), with a number of industry-led (and co-supervised) MSc projects and bursaries
- support for PhD students to attend modelling camps and national/international Study Groups

v. Exploring mechanisms for enhancing public engagement and mathematics communication
Public engagement has followed a similar trajectory of increased activity. There is an active programme to make mathematics, in particular the research activities of the UoA, accessible:

- *Making Maths @ Manchester* – an annual residential course for year 12 and 13 students
- *Magical Books* – a series of eLecture courses, with hyperlinked lecture notes, which have been developed principally for CPD work (KTA grant £55k)
- *Alan Turing Cryptography Competition* – an annual competition for students up to year 11 with industrial sponsorship from Skyscanner (over 1900 entries in 2013)
- *Maths Busking* – bringing advanced mathematics to the streets and shopping malls (HE-STEM support £10k)
- *Meet the Mathematicians* – annual year 12 and 13 day of research talks embedded within the British Applied Mathematics Colloquium (joint with Southampton; EPSRC PPE grant £77k)
- *How to Talk Maths in Public* – a workshop by mathematicians for mathematicians to offer training in all aspects of mathematics outreach (EPSRC PPE grant £25k)

vi. Exploiting all existing organisations and networks, as well as industrial contacts The UoA

maintains close contact with many partners to promote impact of its research, as highlighted in (iii) above, including the Knowledge Transfer Network for Industrial Mathematics. The UoA has exploited all of the KTN's activities on offer to enable interactions between mathematicians and a wide range of users. These include support for two Faraday PDRA awards, and more recently a CASE studentship, 7 sKTPs and 3 KTPs.

Of particular note is the UoA's aim to develop and maintain long-term strategic alliances with key industrial partners through 'hub' support. This offers companies flexibility and a '*one-stop shop*' for their research needs. Current close partners include NAG, Thales, AWE and the MathWorks.

Supporting and enabling staff Inducements for UoA staff to engage with external users include the availability of MAPLE fellowships offering sabbatical leave or teaching relief; introductions to companies via study days; guaranteed support for students and interns on external projects; grants to pursue collaborative research with external users from the School's research arm, the Manchester Institute for Mathematical Sciences, via overhead reinvestment. Additionally at least 85% of income generated from commercialisation goes to the investigators.

In addition, knowledge transfer and outreach activities are part of the assessment criteria for promotion cases, ensuring that staff time on such work is properly recognised and rewarded. Indeed, it can now be the main criterion for such cases. In the last two years 6 members of staff were promoted with a substantial element of impact-focused research activity.

Institutional facilities New campus buildings provide one tangible reason for the step-change in increased inter- and intra-actions. All aspects of the School's activities take place within the bespoke and fully integrated Alan Turing Building, thus allowing, say, the numerical analysts to interact with statisticians, and continuum mechanics researchers to work with pure mathematicians as well as experimentalists. Regarding the latter, a key facet of the UoA is the Manchester Centre for Nonlinear Dynamics (MCND), which facilitates combined experimental/analytical activities between the Schools of Mathematics and Physics & Astronomy via provision of laboratory space, equipment and technician support. The consequent holistic approach to problem solving has recently been successful in attracting industrial funding (£157k) from BP, Kraft Food and Cambridge Display Technologies. Further, the UoA can call on the UoM Research Institute, founded in 2012 to nurture and support interdisciplinary research, and UoM Intellectual Property (UMIP), which offers commercialisation advice and support through the £32m UMIP Premier fund.

c. Strategy and plans

The research strategies of the University, Faculties and Schools are captured in annually updated documents with shared structures, themes and goals. University strategies that emphasise impact within the research goal include *ensuring that translational research is given parity of esteem with basic research*, and within the social responsibility goal that we *advance public engagement with science and technology*. The University agenda provides a framework for specific UoA plans.

The 2010 International Review of Mathematical Sciences stated that "*The UK is widely recognised to have had, for a long time, pioneering and innovative activities in industrial mathematics* […however …] *since the problems faced by industry are constantly changing, flexibility and adaptability are equally important in the long run.*" The UoA has a long history as, and aspires to continue to be, a centre of excellence for industrial engagement and for the development of *best practice* for the impact (in the broadest sense) of its research activity. It has recognised that the endemic problem of narrow UK PhD training has, in recent years, led to broader difficulties of industrial engagement by the academic mathematics community, particularly due to the rapid increase in application areas that demand a rich and diverse set of skills.

Strategy since 2008 The impact strategy has evolved significantly over the REF period. Clear mechanisms for effecting the strategy, and measurable results, are described in (b). *Aims are to:*

- *increase industrial engagement in ongoing research activities, especially with PhD students*
- *provide mechanisms for maintaining long-standing non-academic contacts*
- *provide mechanisms that encourage new engagements in industrially relevant applications*
- *increase communication of mathematics with school students and general public*

The UoA's policy of *rewarding excellence* has meant that interdisciplinary groups have grown when they offer real opportunities for links to external academic or non-academic users. In this regard, recent lectureship appointments have been made in finance/actuarial sciences (3), industrial

mathematics (2), imaging (2), numerical analysis (3), probability (1), and tropical geometry (1).

Future Plans To build on significant recent success, the UoA is keen to expand its activities still further. It has a clear strategy for achieving this in coming years including the following.

- *Industrial Board* The increasing scale of activities requires better oversight and planning for all our industrial and impact work. To achieve this end the UoA is setting up an Industrial Board, composed of leading members from Industry and governmental organisations.
- *Critical Interdisciplinary Appointments* These will continue, with commitment already secured for new lectureships in industrial mathematics (Assier plus 1 other) and one in experimental continuum mechanics. In the core discipline, funding is secured for 2 lectureships in pure mathematics and a chair in statistics for candidates who have the potential for or experience of working across traditional boundaries.
- *Knowledge Transfer* Evatt's activity in industrial liaison will be significantly enhanced by the new industrial mathematics appointments and the MAPLE supported Technology Translator.
- *Industrial Support* The UoA's successful strategy for impact is built around establishing and maintaining long-term partnerships and offering flexibility to users. It aims to use industrial income innovatively (e.g. 2 of the new lectureships are partially supported by industry), to increase industrial support for postgraduates, and to secure further Industry Fellow positions.
- *Key disciplines* The UoA aims to increase impact through the prioritisation and growth of key research areas. As an example, the biotechnology sector is recognised to offer enormous opportunities for mathematical input, and so to address these the UoA has recently recruited Jensen, who has a BBSRC Industrial Partnership Award supported by Syngenta (to model lateral plant root growth, ~£.5m). Other likely areas for further development include complex materials characterisation (biological tissues and industrial composites, in partnership with other Schools and the National Graphene Institute), inverse problems and imaging, and defence.
- *PG training* A fundamental aspect of the UoA's strategy on impact is enhanced PhD training, especially in regard to communication, problem solving and modelling skills. This will enable the students to engage with mathematicians in other areas of research, with non-mathematicians in other academic disciplines, and with non-academics. To this end the UoA will adapt taught course elements of the new MSc Programme in Applied Mathematics (with an Industrial Mathematics focus), exploit existing industrial links, and provide support for a '*global ambassador scheme*', whereby PhD students will play an active role in international Study Groups.

Engagement A further area for a development strategy is public engagement. Sources of funding have, traditionally been modest, and although the UoA has increased its range and level of activity since 2008, there is room for greater involvement of staff members and a greater diversity of communication routes. MAPLE offers opportunities for training and support to staff and this will be exploited in coming years. Development of outreach material for dissemination on the Internet is a planned area of growth. The '*Magical Books*' pilot project is at the forefront of the technology and the University eLearning team is active in promoting recording and preparing podcasts of lectures.

The UoA's strategy will develop over time, as the success or otherwise of activities and initiatives can be documented and analysed. The UoA will continue to develop the virtuous circle, of application outside academe informing novel areas of research informing impact to users.

d. Relationship to case studies

Higham and Tisseur's impact case studies arose naturally through the long-standing relationship between the numerical analysis group and NAG, which dates back to the 1990s, although activity has been significantly enhanced by two recent KTPs and CASE awards. Similarly, Abrahams and Parnell's case is as a result of a long association with Thales (8 students funded), although it has been aided recently by the presence of the Thales Industry Fellow within the School, which motivates the aim of funding more Industrial Fellowships. Lionheart's and Donev's cases would not have been achievable on such short timescales without the use of KTP and KTA funds to support the development of impact, and without PhD students being able to take up Internships, motivating the strategic enhancement of PG student training. Laycock's case is historic and therefore not influenced directly by impact strategies developed throughout the REF period.