Institution:
The University of Sheffield
Unit of Assessment: 12A - Aeronautical, Mechanical, Chemical and Manufacturing Engineering: **Mechanical Engineering and Advanced Manufacturing**

a. Overview

This unit comprises the Department of Mechanical Engineering, the Advanced Manufacturing Research Centre, and academics from Cardiovascular Science. The unit has seen unprecedented growth and success since 2008: the number of staff submitted has increased by 48%, PhD student entry has increased by 90%, and research income (REF4b) has increased by 200% to £27M. The unit's research is classified into five research themes:

- **Dynamics** focuses on structural health monitoring, nonlinear systems, vibration, and damping.
- **Manufacturing** comprises the Advanced Manufacturing Research Centre (AMRC) and new activity focusing on additive manufacture. The AMRC is a leading research centre for advanced manufacturing with over 70 industrial partners, and became a separate cost centre in 2008.
- **Thermofluids** includes the Low Carbon Combustion Centre (LCCC) which houses unique pilot scale facilities for carbon capture and combustion research. This is complemented by expertise in turbulence, computational fluid dynamics, and nuclear thermal hydraulics.
- **Solid Mechanics** comprises broad expertise in tribology, experimental mechanics, composites, and computational mechanics.
- **Bioengineering** is a substantial new group focusing on engineering modelling for healthcare, including colleagues (Hose & Lawford) from Cardiovascular Science. Here, we lead the Institute for In-Silico Medicine (INSIGNEO).

Our collaborative work frequently cuts across these themes, using application-focused teams and research centres to ensure that our research addresses the key challenges facing society.

b. Research Strategy

b1. Forward vision

The vision of the unit is: to apply our core strengths in mechanical engineering science to tackle the key challenges facing society; to advance fundamental science; and to achieve stakeholder impact. Within each theme, our vision leads to the following plans:

- *Dynamics* aims to improve the dynamic performance of engineering structures for key technology sectors such as energy generation and aerospace engineering. To achieve this, our strategy will be to develop and apply mathematical tools (e.g. machine learning, statistics), coupled with rigorous experimental techniques, to tackle industrially relevant problems.
- *Manufacturing* aims to change how and where products are made by conducting research into established and emerging manufacturing technologies and applying this to high-value products across sectors ranging from aerospace to consumer products. The AMRC will achieve this by continuing its industry-facing research with particular emphasis on machining and composites for aerospace and nuclear sectors. Meanwhile, fundamental research will focus on advances in machining science, and additive manufacture of novel bio-compatible and functional materials.
- *Thermofluids* aims to support global aspirations for secure, low carbon, and sustainable energy. To achieve this we will perform both fundamental and applied research in combustion and fluid mechanics. Our focus will be on aviation fuels, carbon capture, nuclear thermo-hydraulics, turbulence, and computational fluid dynamics.
- *Solid Mechanics* aims to combine experiments and analysis using advanced simulation approaches to provide the new tools and devices that will support the development of components, structures, and processes for growth and competitiveness across sectors. We will focus on our core strengths (e.g. tribology) and combine this with new expertise from recently recruited staff so as to explore new concepts and gain access to more industrial sectors.
- *Bioengineering* aims to produce a transformational impact on healthcare through the development of an integrative modelling and software framework able to diagnose, predict and guide in the treatment of pathologies. Our strategy will be to focus on developing and implementing the most effective tools for computational fluid dynamics, finite element analysis and image processing, and to link this with clinical needs through cross-disciplinary work.

b2. Leadership strategy

During the period 2008 to 2013 we have seen unprecedented growth as illustrated in Section b3. Consequently, our strategic focus over the next period will be to maximise the research potential of existing staff whilst continuing to recruit based upon talent. In particular, we aim to maximise opportunities for inter-disciplinary research, by enabling expert teams to evolve that work collectively across discipline boundaries. We will also ensure the best possible environment for implementing research activity, and nurture the potential of new and early-career academic staff, by providing academic leadership and extensive non-academic research support.

The foundations for this strategy have already been laid through a substantial investment in support staff, research equipment, and management structure. Consequently over the next 5 years we will focus on our physical and social environment, to maximise the opportunities for collaboration, whilst providing the best infrastructure for delivery of our experimental research, and ultimately providing an inspirational environment through which we can realise our research vision.

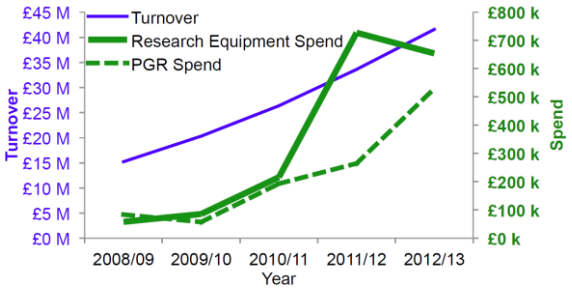
As a result we have an ambitious £200M building programme across the Faculty and AMRC. These infrastructure plans are described in Section d1.

b3. Progress against RAE 2008 plans

In 2008, our ambition was *"to extend our outstanding core engineering science expertise and use it to conduct ground-breaking research to the benefit of society, manufacturing industry and the knowledge economy"*. Our strategy to achieve this was *"to appoint talented staff from engineering, mathematical and science disciplines and nurture multi-disciplinary teams in a supportive and inspiring environment."*

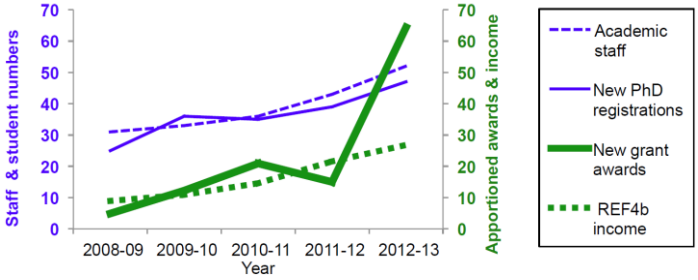
Overall, we have hugely exceeded these expectations, with a net increase of 22 academic staff, and the formation of a new research group (Bioengineering). Annual turnover has doubled, enabling us to substantially increase our support for research now and in the future. Over the assessment period we spent £1.7M on research equipment, and £1.1M to support postgraduate research students. This investment is sustainable: in 2012-13 we set aside £1.4M for future years. The year-on-year growth in this annual investment is illustrated in Figure 1.

Figure 1: Turnover and Investments



At the AMRC the growth is encapsulated by continued infrastructure developments: the Nuclear AMRC (2010), an extension to the Factory of the Future (2012), and a £10M HEFCE award (2013) for the £43M 'Factory 2050'.

Figure 2: Growth in research activity



This investment and growth has led to an immediate increase in research activity even when compared to the increase in academic staff, as shown in Figure 2. This success is echoed across the Faculty of Engineering: total research income has become the second highest in the UK (2011/12 HESA; THE June, 2013), with total turnover increasing from £78M to £105M.

b4. Specific research achievements since RAE 2008

Dynamics: *Our RAE2008 plans focused on uncertainty modelling and structural health monitoring.* We hosted the 2nd International Workshop on Uncertainty in Structural Dynamics (2009), and the workshop has subsequently become a prominent component of the International Conference on Noise and Vibration Engineering (2010, 2012, and 2014). Work exploring uncertainty analysis for 'shaken baby syndrome' led to an IMechE prize, and we continue to explore uncertainty propagation in biomechanical models via a Leverhulme grant. Advances in structural health monitoring using econometric tools, published in Proc. Royal Society, led to a Structural Health Monitoring Lifetime Achievement Award, and an EPSRC Fellowship. Furthermore, a renewed emphasis on nonlinear dynamics led to the award of the Journal of Sound and Vibration Doak prize, and an EPSRC Programme Grant.

Manufacturing: *Our RAE2008 research plans focussed on manufacturing with new generation materials for lighter, stronger and more efficient machines*. We developed new understanding on the machining of aerospace materials such as titanium and heat resistant super-alloys that was recognised by an IMechE best paper prize. Application to combustion casing machining with Rolls-Royce has enabled a step change in productivity and helped to justify investment in a new UK factory. Meanwhile, Network Rail funded research into high speed rail grinding (using super-abrasives), has become the sector benchmark, and the results are now included in Network Rail tender documents for the next generation fleet of grinding trains. Furthermore, the AMRC was awarded Boeing's International 'Supplier of the Year' award in 2010. The AMRC was selected from a pool of more than 17,500 Boeing suppliers in 50 countries, in recognition of a world class facility that has delivered technology-driven advanced manufacturing solutions to the Boeing supply chain.

Thermofluids: *Our RAE2008 research plans focussed on biofuels, flow control, and modelling*. We have successfully developed models of biofuel behaviour that were subsequently implemented by the European Network of Excellence to produce a unique database of aircraft emissions. Meanwhile, we continued to disseminate fundamental findings concerning turbulence; we invented novel shock control bumps that are being further developed by Airbus; and our novel zipper layer CFD method has enabled Rolls-Royce to patent designs for aero-engine components. Furthermore, LCCC has been established as host of the national Pilot-Scale Advanced Capture Technology facilities (£1.9M grant from DECC and EPSRC). This is the national specialist centre for combustion and carbon capture technology research.

Solid Mechanics: *Our RAE2008 research plans were broad, including a focus on human interaction with devices, and innovative sensors for monitoring engineering structures*. Research on human interaction has revealed the relationship between skin structure and finger-pad friction, using Optical Coherence Tomography. This is continuing with an EPSRC project in collaboration with Philips and Unilever. We have developed unique ways to measure lubrication in auto-engines as part of an EPSRC Programme Grant (Encyclopaedic, £470k to Sheffield). This has helped an industrial collaborator develop piston rings that consume 40% less oil. We also expanded into the wind turbine field with £300k of funded projects on design and monitoring of gearbox bearing systems. Against a background of staffing changes in this area, nine new staff have brought complementary expertise in finite element modelling, fracture mechanics, and composites.

Bioengineering *Bioengineering applications featured across many of our RAE 2008 aims*, and in 2008-10 we developed a new strategy to promote this activity, with substantial investment in international staff (see Section c). Consequently, two academics from the Department of Cardiovascular Science are included in this submission: their work at the interface between engineering and medicine reflects our ambition to translate engineering modelling into clinical applications. The Bioengineering team has rapidly had an international impact, particularly in cardiovascular biomechanics. Research performed at Sheffield includes the development of a model of intracoronary physiology, which uses angiograms from patients with coronary disease to create models to predict the pressure gradient across diseased arteries. The resulting system improves clinical outcomes and is to be trialled on 100 patients from South Yorkshire.

c. People, including:

I. Staffing strategy and staff development

We aim to recruit, develop, support, and reward staff to achieve their maximum ability. In the 2012 University wide staff survey, Mechanical Engineering scored highly for staff satisfaction with 90-100% positive outcomes for items such as personal development, commitment to goals, pride in employment, and sense of value.

Culture and management

Institutional and local support for research has helped us to achieve the *"supportive environment"* described in our RAE 2008 strategy. This has been partly enabled by the University adopting a new faculty structure in 2008, which has allowed us to re-invest funds to support research. The Faculty has invested £6.4M in cross-faculty research support, including a network of ten Business Development Managers and associated staff in the Faculty of Engineering Research & Innovation Hub (FERIH). In addition, the University has appointed a Research Director with a specific remit for research collaboration with the AMRC. This has attracted interest from more than 100 academics

to actively engage in collaborative cross-themed research. In Mechanical Engineering, we also established two new support posts for Business Development and Post Award management. These staff liaise with their counterparts in other Departments and have a functional link to FERIH.

As well as this support for research, we have aimed to maintain an "*inspiring environment"*, with a culture of research excellence and ambition. We have adopted the following approaches:

- Academic staff are returned 20% of research grant overheads to spend at their discretion, thus recognising their achievements and pump-priming new research ideas.
- We have an annual allocation of core funds for strategic research equipment. This focuses on equipment that brings new capability, new collaborations, or opens up new research areas (examples are detailed in Section d).
- We implement annual Research Away Days, which focus on new research ideas.
- We pioneered 'red-lining' weeks for grant writing, where all other activity is suspended so that academic staff can focus on formulating new research plans. This helped, for example, Carre and Lewis to work on their successful EPSRC project proposal. The approach was later emulated across the Faculties of Engineering and Science.

Our research ambition includes a desire to inform the wider public of our achievements, which has resulted in 34 press releases over the period.

Recruitment and staff development

Aligned with our RAE 2008 ambition to *"expand our expertise by appointing talented staff,"* recruitment has been key to our staffing strategy. We have targeted the very best early career staff and look for ambitious, intelligent and motivated individuals with the capability to set their own research agenda. Early career academics and recruited lecturers are subject to a three year probation process which sets ambitious targets for research grant capture (£100k per year), PhD recruitment (1 per year), and publication (2 papers per year). Staff are supported to achieve these targets with the allocation of a minimum of one funded PhD student, a research mentor, start-up funding, a light teaching load, and no admin duties. This has meant that, despite challenging targets, all eligible staff have successfully passed their probation during this period.

Since 2008 we have recruited 21 excellent first time lecturing staff. Whilst some of these have been very recent appointments, others have already demonstrated their potential: Fletcher is Sheffield PI on 5 FP7 projects (totalling £1.6M), runs the Rail Innovation & Technology Centre (funded by Network Rail) and was promoted to SL; Marshall has initiated new collaborations with Rolls-Royce, been awarded £700k in external funding, helped to secure the IDC in Machining Science, and was promoted to SL. More recent starters have achieved grant awards as Principal Investigator: KTPs for Slatter, Rowson and Cross; Royal Society Research Grant for Slatter, EPSRC First Grants for Gitman and Smith; and a Leverhulme Trust Project for Rowson.

We have also looked to augment our team of research leaders, successfully recruiting a further 9 international research-leading chairs to establish new groups or complement existing expertise. Overall, this recruitment of academic staff has led to the following growth in each research theme:

- In **Dynamics**, the appointment of three leading Professors (Cartmell, Horoshenkov and Wagg) together with four other academic staff has consolidated our position as a leading centre for research on nonlinear effects, and provides new expertise in acoustics.
- In **Manufacturing**, four academic staff were recruited, including Hopkinson who leads the University Centre for Advanced Additive Manufacture (AdAM).
- In **Thermofluids**, two Professorial (He and Zhang) and one other appointment have brought expertise in nuclear applications, combustion and turbulence.
- In **Solid Mechanics**, the recruitment of nine academics underpinned two new University research centres: the Leonardo Centre for Tribology and Surface Engineering, and the Rail Innovation & Technology Centre.
- In **Bioengineering** we identified an area with huge potential owing to our collaborations with Cardiovascular Science. Our aim to grow this activity led to the recruitment of seven academics including international research leading Professors Viceconti (President of the European Alliance for Medical and Biological Engineering & Science), Lacroix (Holder of an ERC Fellowship), and Frangi (PI of over 20 national & EU Projects).

Our implementation of the Staff Review and Development System (SRDS) is a natural extension to the probation process, and carries through clear and stretching research objectives for all staff, reviewed by the HoD or a line manager. SRDS objectives for academic staff are set against strategic goals, linked to Faculty wide metrics and career progression. In the REF period, 8 staff were promoted to Senior Lecturer/ Reader and 4 staff were promoted to Personal Chairs. A key aspect of SRDS is the identification of training and development needs. Our flagship training scheme 'Sheffield Leader' forms a series of eight-day training courses, which are undertaken at four levels from RA to Senior Professor, preparing staff to lead research activity and groups.

Research staff

Research staff have access to mentoring and development opportunities in the same way as academics, and are encouraged to take part in the management of the unit. Training is reviewed annually through the SRDS, and every senior staff member has an SRDS objective to develop their key researchers towards lectureships or fellowships. Support and coaching for competitive fellowship schemes are also provided by the Director of Research.

Our long serving RAs are all on open ended contracts, paid from research grants, but underwritten by core funds. Meanwhile, our 'Fellowship to Lectureship' scheme automatically considers researchers with prestigious fellowship awards for an open-ended Lecturer position at the end of the funding period. The Engineering Researcher Society (ERS) provides opportunities in the form of bursaries for professional development and a community for social and research networking events and the Sheffield 'Think Ahead' programme provides a comprehensive blend of training workshops, career mentoring, and selected work-based opportunities.

As a result of this support, in the Careers in Research Online Survey (2012) 86% of our contract researchers agreed or agreed strongly that they are encouraged to take part in personal and career development against a sector average of 73%. Meanwhile, since 2008, 7 research staff have been recruited as Sheffield lecturers in open competition and many more have pursued successful careers elsewhere (e.g. Patsias – Rolls-Royce; Beke – Messier-Dowty; Green - Shell; Reddyhoff - Lectureship at Imperial College). Furthermore, the University achieved the European Commission HR Excellence in Research award (2012). This signifies that we have a high quality research environment for ECRs and acknowledges alignment with the UK Concordat for the Career Development of Researchers' 7 Principles.

Fellowships, exchanges and visits

We encourage staff to collaborate widely and have a programme of rotating sabbaticals which have resulted in collaborations with various international institutions. As described in Section e, two staff held RAEng Industrial Secondments during the period, two staff held prestigious EPSRC fellowships and we hosted two RAEng Distinguished Visiting Fellows. A further staff member has been seconded for three years to take on the role of Research Director at AMRC with a remit to establish new research avenues and collaborations. We also have a healthy number of visiting scholars and a permanent team of seven contracted Visiting Professors and Advanced Visiting Fellows from industry (Ricardo, EDF, Airbus, DSTL, Philips, Fiat CRF, Rolls-Royce) with whom we develop new research strategies and collaborative projects.

Equality of opportunity

We support and recruit the best academic and research staff regardless of their race, gender, nationality, sexual orientation, or religion. We have a balanced demographic, both in terms of seniority (29% Chair, 22% SL/Reader, 49% Lecturer) and internationalisation (57% UK, 23% EU, and 20% from other nations). The Faculty has also made a high level strategic commitment to be a place of choice for women to work; the Department of Mechanical Engineering fully reflects this aim and the Faculty Director for Women in Engineering is a Professor within the Department. In partnership with other Faculty of Engineering Departments specifically through the Women in Engineering initiative we are taking positive actions and making investments to increase the number of female academics, researchers and students. To demonstrate our commitment we have formed an Athena Swan Self-Assessment Team (led jointly by two Department Champions, male and female) to work towards achieving a Silver Athena Swan Award. Over the past two years our efforts have allowed us to a double the number of female academic staff in Mechanical Engineering from 5 to 10.

c. II. Research students

We recognise that research students are at the core of our activity as a research-led unit, so we have focussed on recruiting the best students and training and developing them effectively.

Recruitment. To identify and recruit the best students, we implemented a 'rapid response' selection and offer process with a Postgraduate Admissions Tutor, full time clerical support, and a Scholarships Officer, to streamline access to funding. Although we expect academic staff to generate the research funding to employ PhD students, this is supplemented by full- or part-funded studentships, with priority given to new academic staff. Over the period, in addition to Research Council and University/Faculty Scholarships, we have used £1.1M from core budgets to fund or co-fund 25 PhD students. We have also created an Industrial Doctoral Centre in Machining Science funded through a £1.2M grant from EPSRC, operated jointly between Mechanical Engineering and AMRC. The programme offers enhanced stipends (£17-18k) to attract the best candidates; the students explore key manufacturing challenges whilst having access to a high quality scientific research base and state of the art technologies.

As a result of this effort, the annual PhD student intake has risen from 22 in 2008 to 52 in 2013, which will lead to year-on-year increases in the number of doctoral degrees awarded per staff FTE. We plan to continue this recruitment success, partly underpinned by the successful award of EPSRC Centres for Doctoral Training in Tribology and (as a renewal) Machining Science.

Training and development. We have a rigorous supervision and monitoring process for all PhD students, monitored by a dedicated Post-Graduate Tutor. Each student has two supervisors who are required to meet formally at least monthly (though in reality meetings are much more frequent). At the end of Year 1 we have a formal confirmation of candidature process consisting of the submission of a progress report, a presentation, and a viva. At the end of Year 2 students create a "thesis completion plan" (annotated contents page and updated Gantt chart).

Sheffield has pioneered an innovative approach to doctoral training: the Doctoral Development Programme (DDP). The process commences with the student and supervisor carrying out an individually-tailored training needs analysis, from which a bespoke training programme is designed. The DDP is a flexible, on-going training plan that is an integral part of a research degree, and is tailored to individual needs. The aim is to provide research students with a range of skills and competency-based training opportunities focused on enhancing their specific study and equipping them with transferrable skills that extend their employability.

All PhD students have their own desk in secure well-equipped shared offices and are made to feel valued and respected as part of an inclusive environment. We organise regular social occasions including a monthly 'Coffee and Cakes' event for all staff and PhD students.

As evidence of our successful approach, five of our PhD students were awarded EPSRC/University Doctoral Prize Fellowships which provide one year's salary and research expenses to pursue an independent research project after their PhD. Two are now lecturers in the University, and one has a Medical Research Council Fellowship.

d. Income, infrastructure and facilities

d1. Research Infrastructure Plans

Over the next 5 years, improving our infrastructure will be a central aspect of our strategic plans. This forms part of a University-wide £250M capital plan, with £154M committed to the Faculty of Engineering for the period to 2010 to 2015.

The **Engineering Graduate School Building** (£21M) will open in Dec 2013, providing 5,355m^2 of laboratory and office space for three collaborative interdisciplinary research groups and teaching space for postgraduate taught and postgraduate research students. The building will house many of the bioengineering activities from our unit (964m^2 net internal area), and postgraduate research students from across the Faculty will use the building's resources.

The **New Engineering Teaching Building** (£81M) will create by 2016 a purpose built teaching space occupying 19,500m^2. This relocation of teaching laboratories will create space in Mechanical Engineering to accommodate new research labs, academics and research staff.

An integrated **atrium** (£9M) will provide new space (2,800m^2) between our existing buildings, for both circulation and collaborative working. Alongside this a further £9M will be spent on **complete**

refurbishment of the Mechanical Engineering Department Central Wing (3,300m^2) to provide higher quality laboratory and office space. Together, the atrium and refurbishment projects are central to the achievement of our plans for an inspirational environment for cross-disciplinary and collaborative research. These developments are part of a £53M investment from the University, which facilitates the major refurbishment of 12,000m^2 of our current Faculty of Engineering estates.

Meanwhile, the AMRC has secured £43M (including £10M from HEFCE) for a new 4500m^2 faculty to be built in 2014. **Factory 2050** will be the UK's first fully reconfigurable assembly and component manufacturing facility for collaborative research.

d2. Research infrastructure investments since 2008

Our building plans will involve substantial reorganisation of space across the Faculty. To facilitate this we have installed a temporary 'Modular Research Village' (1400m^2, £1.4M), comprising research laboratories, academic offices and research assistant work rooms.

To accommodate our increase in size, we invested £2.1M in refurbishing the **Garden Street Building** for use as research labs (500m^2) and offices (for 9 academics and 36 researchers). This is used by AdAM (Advanced Additive Manufacturing) and composites researchers. In addition to this, over the last 5 years the University has also invested a further £6.1M in to the main Engineering campus, to maintain buildings (£2.5M) and provide office accommodation (£3.6M).

Over the period AMRC has expanded significantly with the £10M 4,500m^2 Rolls-Royce Factory of the Future (2008, 1,800m^2 extension in 2012 for the Composite Centre), and the £15M 8,000m^2 Nuclear AMRC (2009, with a further £37M grant in 2012). The AMRC has also received a £9.2M award from the Regional Growth Fund to create a 5,500m^2 Training Centre; an 830m^2 Knowledge Transfer Centre has been created with conferencing facilities for 200 delegates; and there is a 5,500m^2 Design and Prototyping Centre.

Other improvements to the quality of our infrastructure include:

- Refurbishment of LCCC main site at Beighton funded by a £315k Wolfson grant enabling improvements to the laboratory environment and more office space to accommodate growth.
- A new 280m^2 lab has been created for the Leonardo Centre, with facilities for testing of friction, wear, lubricant performance, and oil films.
- A new 230m^2 lab has been created for the Human Factors research, including sports engineering, human dynamics, and haptics.
- A new 80m^2 cell culture lab has been established creating a unique facility to research the mechanical aspects of biological tissue at cellular level.

d3. Research facilities

Over the period we have invested heavily in research facilities and equipment. The following are some of the major investments funded from core budget (totalling £1.7M) in addition to the routine purchase of equipment within research grants.

- New Mechanical Engineering workshop facilities (£180k) including a 5 axis machining centre, six new milling machines and lathes, and a Faro 3D laser scanner.
- We have greatly improved our main materials testing laboratory with £215k to refurbish machines, upgrade the servo-hydraulic supply, and for new instrumentation including a state-of-the-art 3D Digital Image Correlation system for full field strain measurements.
- Additive manufacturing equipment for the new AdAM Centre (£500k), including a JetLab multi-material inkjet printer, an Objet Eden 260V Multijet Additive Manufacturing machine, and Laser Sintering / High Speed Sintering Machines.
- Dynamics and metrology test equipment (£256k), including a CETR tribometer, a Perkin Elmer Differential Scanning Calorimeter, a Melt Flow Indexing System, and laser vibrometers.
- Flow testing systems (£135k), including a Particle Image Velocimetry system, a Laser Doppler Velocimetry system, and a new wind tunnel (£25k).

Meanwhile, the AMRC has a unique range of specialist facilities for manufacturing research, including a £2M Ecospeed Machining Centre, a £1.9M Starrag STC 1250, and a £1.8M Mori-Seiki NT5400 mill/turn machine. Composite manufacturing facilities include a £300k curing press, a £300k robotic filament winding machine and two autoclaves.

High performance computing facilities have been continually upgraded over the period, with over

£250k invested from the unit to enable dedicated access to over 800 CPU cores. In total, £2M has been invested in the University's facility to provide over 1500 cores and 125 Terabytes of storage.

To achieve our vision of providing the best possible environment for research, our plans are to spend 10% of our annual core budget (typically £500k) on stimulating research. This will be in the form of funded PhD studentships, equipment, and other pump priming activities. In addition, we have a new Faculty initiative to stimulate ambitious plans for capital research equipment, to include an annual cycle of support activity aligned with the annual financial planning round.

d4. Research award portfolio and plans

The unit has a diverse portfolio of research funding over the period (as evidenced by our REF4b data), and the breadth of industrial sponsors is indicated in Table 1. Whilst Boeing and Rolls-Royce feature prominently in the AMRC's industrial funding portfolio, our Research Council funding is spread across research themes:

Sponsor	Award
Rolls-Royce	£10,981k
Boeing	£4,158k
Siemens	£883k
Airbus UK	£875k
Qatar S&T Park	£825k
Network Rail	£566k
Tata Steel	£509k

Table 1: Top industrial sponsors, based upon grant awards 2008-13

- We were awarded the EPSRC funded £4.2M programme grant "Engineering Nonlinearity" (jointly with Bristol). This is the UK's leading consortium of Dynamics based research activity, consisting of 5 University and 8 industry partners.
- Worden was awarded an EPSRC established career fellowship that uses healthcare informatics for the monitoring of populations of structures.
- In 2012, we were awarded an EPSRC Frontier Engineering Award (£5M to Sheffield) on Modelling Complex and Partially Identified Engineering Problems. This will develop multiscale studies in bioengineering to make a transformational impact on healthcare.
- The Institute for Microstructural and Mechanical Process Engineering (IMMPETUS) has been awarded two major EPSRC grants over the period: an £880k Platform grant (2007-12), and a £4.5M research grant (2008-12).

Our **research funding plans** are to focus on large funding opportunities in research topics where we can demonstrate a critical mass of expertise. We expect the new expertise in bioengineering, additive manufacture, and dynamics/acoustics feature heavily in our future portfolio, and that new synergies will result in funding growth for research work across discipline boundaries. Although we plan to maintain a diversity of income streams, and a cross-sectorial profile of industrial sponsors, we see Horizon 2020 as a significant opportunity where we can build even greater levels of participation. Through the FERIH business development support we have access to specialist expertise in EU funding mechanisms, and this is complemented by strong academic presence in bioengineering (Viceconti, Frangi, Hose), transport infrastructure (Fletcher), and low carbon technologies (Wilson). Meanwhile, we will support our ECR staff to become international research leaders. With the engagement of our Business Development Manager we are helping this group to identify opportunities such as fellowships and EU programmes.

We expect industrially-funded research to be an important component of our portfolio, particularly for the AMRC and LCCC. To broaden the industrial participation in other activities, we will draw upon the new network of Business Development Managers provided by FERIH.

d5. Knowledge transfer, consultancy, professional services to industry

The AMRC membership model provides an exemplar service to industry. As described in our impact template, the AMRC includes over 70 member companies, who pay up to £200k per year to steer, participate, and benefit from shared research programmes. The approach has been emulated worldwide, and informed UK Government policy regarding Catapult Centres. We are working to reproduce this successful approach in the fields of bioengineering and combustion. In bioengineering we are collaborating directly with clinicians and National Health Trusts, whilst in the Low Carbon Combustion Centre we house unique pilot scale facilities that are available to industry through the spinout company EPTeC.

Academics from across the unit are encouraged to consult, and the University provides simple and efficient procedures to handle all administration and invoicing. Consultancy income over the period was £525k, and on many occasions (for example work with Unilever WD40, Buhler-Sortex, Messier-Dowty, EDF, Caterpillar) consultancy has led to longer term relationships and projects.

e. Collaboration and contribution to the discipline or research base

e1. Exemplars of research collaborations

The AMRC is an exemplar of *world leading collaboration between a university, industry and key government offices*. The centre is focused on advanced manufacturing and materials research for aerospace and other high-value manufacturing sectors, and has over 70 industrial partners ranging from global aerospace (Boeing, Rolls-Royce) and nuclear manufacturing giants (Westinghouse, Tata) through to local SMEs. Researchers work with individual companies on specific projects, and collaborate on generic projects for the benefit of all members.

The LCCC is another exemplar of *collaboration with industry*, and is designed to bridge the gap between bench scale and industrial pilot trials in combustion and fuels research. The Centre has carried out a range of industrially funded research programmes with RWE Npower, E.On, Rolls-Royce, Unison Engine Components, Shell, BP and the Energy Institute.

The INSIGNEO Institute exemplifies *interdisciplinary research* as a collaboration between the Faculties of the Engineering and Medicine, and Sheffield Teaching Hospitals NHS Foundation Trust. INSIGNEO, founded in 2011, and led by Mechanical Engineering now has over 100 affiliated academic staff from engineering (45%), clinical departments (25%), cardiovascular science (15%) and computer science (15%). Its goal is the achievement of the Virtual Physiological Human initiative: the widespread introduction of in-silico (computer simulation) techniques into diagnosis and treatment of disease. The outcomes of INSIGNEO's healthcare research projects are typically two-fold: predictive software simulation systems for use in the clinic, and interventional mechanisms that are personalised to the patient. In both cases, academic teams collaborate intensely with clinicians who inform the research and specify required outputs, and with industries that will both engineer the final software systems and produce the patient-specific intervention.

Our bioengineering research also exemplifies *international collaboration*. For example, we are coordinating the EU grant Dementia Research Enabled by IT (€3.5M), which involves 21 partners from 10 countries across Europe. The aim is to develop new imaging techniques to study aging and dementia. We are also coordinating the VPH-SHARE project, which aims to provide a collaborative environment for sharing data, knowledge, and models related to the Virtual Physiological Human.

e2. User-driven research strategy

The AMRC's research activity is almost entirely driven by the needs of its industrial partners. This is achieved through close relationships at both a senior managerial and at practitioner level. Rolls-Royce permanently locate staff at the AMRC, so that there is a daily input from research users to the short-term research strategy. Meanwhile, Technical Fellows Conferences take place every 6 months; they are used to disseminate findings from on-going projects and to discuss new concepts with industrial partners. Our IDC studentships are formulated with this industry-driven approach. Finally, formal planning takes place via the Board of Industrial Partners with input from key academic staff to determine the longer term strategic aims for the Centre. Collaboration across the unit means that these user-driven challenges can frequently lead to EPSRC funded activity. Examples include new concepts for structural health monitoring of composite materials during manufacturing (Worden *et al*), and process damping during machining (Sims *et al*).

Interaction with end-users cascades throughout our research activity. For example:

- In the nuclear energy sector, our interaction with EDF energy has directly influenced our strategy for both structural and fluid dynamics. For example, EDF's steering committee role for our Engineering Nonlinearity Programme Grant led to their support of a PhD studentship to specifically address one of their research needs.
- A long-standing relationship with Rolls-Royce has shaped our research priorities in manufacturing, dynamics, tribology, and combustion. Example topics include damping technologies, frictional performance of aero engine fasteners, thermal stability of combustion systems, and new computational fluid dynamics codes.
- Network Rail has shaped our research strategy by funding the Rail Innovation Technology Centre. Through this, PhD students are undertaking short secondments with the company to disseminate research to users and to focus further research in areas of maximum need.

e3. Exemplars of leadership in the academic community

National or international advisory board memberships

High Value Manufacturing Catapult Management Board (Ridgway),
Executive Director Virtual Physiological Human Institute (Viceconti),
President of European Alliance for Medical & Biological Engineering & Science (Viceconti),
British Standards Committees for Cardiovascular Implants (Lawford),
Executive Member Rail Research UK Association (Fletcher), REF Panel Membership (Horoshenkov, Cartmell), Academic Advisory Board Offshore Renewable Energy Catapult (Ridgway), Governance Board HSE Long Latency Health Risks (Ridgway).

Leadership roles in industry, research councils, learned societies or professional bodies

32 staff are members/fellows of 44 professional institutions (such as IMechE, RAeS, IoM3, IoP, ESIS); 15 staff are EPSRC college members. Staff have key roles in policy making bodies such as: **IMechE Council (Beck)**, **Vice President International Tribology Committee (Lewis)**, IMechE Tribology Committee Chair (Lewis), Ansys Advisory Panel (Viceconti), Rolls-Royce Technical Committee on Combustion (Wilson), Rolls-Royce Advisory Committees (Ridgway).

Conference organisation and programme chairs

20 staff organised 35 workshops, seminar, or conferences including: International Conference on Uncertainty in Structural Dynamics, International Conference of the IEEE Engineering in Medicine and Biology Society, International Symposium on Biomedical Imaging; International Conference on Deformation and Fracture of Composites and Structural Integrity, International Conference on Contact Mechanics & Wear of Rail Wheel Systems, and one-day seminars for British Composite Society, European Society of Biomechanics, British Heart Valve Society and the IMechE.

Invited keynote lectures

Over 73 invited keynote lectures or talks were given including: International Conference on Computational Bioengineering, Advanced Manufacturing Show NEC, International Society of Biomechanics, Digital Fabrication Conference, Additive Manufacturing Symposium, Materialise-Magics Summit, Railways 2012, Leeds-Lyon Symposium, International Conference on Tissue Engineering, I-FAB 2008 Conference, ITUAM Symposium, BSSM Measurements, International Conference on Energy Systems Engineering, International Modal Analysis Conference.

Election to membership or fellowship of learned societies. **Staff hold 21 elected Fellowships** including: IMechE, Institute of Physics, Institute of Mathematics, Energy Institute, Royal Aeronautical Society, Institute of Acoustics, Institute of Materials Minerals and Mining.

Journal editorships, board membership, special issues

Staff hold 19 positions as Editor-in-Chief or Associate Editor including: Journal of Sound and Vibration, Proc IMechE Part J, Journal of Mechanical Systems and Signal Processing, IEEE Trans on Medical Imaging, Journal of Medical Engineering and Technology, Medical Image Analysis, Journal on Imaging Sciences, International Journal for Computational Vision and Biomechanics. In addition, staff serve on the editorial boards of 32 journals, and have edited 15 special issues.

Externally funded fellowships.

EPSRC Established Career Fellowship (Worden, 2013-18), European Research Council Starting Grant (LaCroix 2010-14), EPSRC Advanced Research Fellow (Sims 2004-09), Marie Curie Post-Doctoral Incoming Fellowship (Dell'Ara 2013-15), RAEng Distinguished Visiting Fellowships (Farrar - Los Alamos; Giurgiutiu - University of South Carolina), and a RAEng Visiting Professor (Wood).

Prizes and awards. 12 staff have won prestigious personal research awards including:
CBE for Services to Manufacturing Research (Ridgway),
Structural Health Monitoring Lifetime Achievement Award (Worden),
ASME Breakthrough Technology Award (Hopkinson), Jean Leray Award (LaCroix), IoP Prize for Innovation in Tribology (Lewis), Royal Society Brian Mercer Award (Horoshenkov).

Paper Prizes

31 papers have won prizes including: Journal of Sound and Vibration Doak award, IMechE Duncan Dowson Prize, IMechE Joseph Whitworth Prize, IMechE Railway Division Premium Award, IMechE Charles Sharpe Beecher Prize, IMechE Railway Division Prize, STLE Frank Bussic Award, Best Paper in Civil Engineering Prize, Rapid Prototyping Journal Outstanding Paper Award, BSSM Best Paper, IOM3 Composites Paper Award, Strain Best Paper.