Institution: University of Strathclyde

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

a. Overview

Since RAE2008 the University of Strathclyde UoA12 Research Strategy has produced sustained growth in all main performance indicators: 171% increase in research income from £4.9M in 2008-09 to over £13.4M in 2012-13; 300% growth in PGR population from 45 in 2008-09 to 183 in 2012-13; 86% increase in staff from 36 in 2008-09 to 67 in 2012-13; and 60% growth in KTP income from £508k in 2008-09 to £814k in 2012-13.

The University of Strathclyde's UoA12 submission comprises researchers from four Departments in the Faculty of Engineering: Chemical and Process Engineering (CPE, 14 FTE staff); Design, Manufacture and Engineering Management (DMEM, 14 FTE staff); Mechanical and Aerospace Engineering (MAE, 23 FTE staff); and Naval Architecture and Marine Engineering (NAME, 16 FTE staff). UoA research groupings and centres all focus on the strategic research themes below that are embedded within the departments:

Advanced Materials & Manufacture: Advanced Manufacturing and Technology; Advanced Forming Research Centre; Biomolecular Engineering; Centre for Innovative Manufacturing for Continuous Manufacturing and Crystallisation; Design Research Group, Nanostructured Materials; Strathclyde Institute of Operations Management.

Aerospace & Marine Technology: Advanced Space Concepts Laboratory; Centre for Future Air-Space Transportation Technology; James Weir Future Fluids Laboratory; Marine Design, Operations & Human Factors; Marine Engineering; Marine & Offshore Hydrodynamics; Space Mechatronic Systems Technology; Ship Stability and Safety; Strength & Reliability of Ships & Offshore Structures.

Energy, Sustainability & Environment: The Industrial Doctorate Centre in Offshore Renewable Energy (IDCORE); Marine & Offshore Renewable Energy; Mechanics & Materials Research Centre; Weir Advanced Research Centre.

b. Research strategy

Our vision is to deliver fundamental and applied research within our core research areas that makes a significant contribution to the research base and leads directly to wealth generation, economic growth, sustainable use of global resources and improved quality of life throughout society.

2008 Strategy: Our RAE 2008 strategy was to:

- Target expertise at technological applications addressing distinct global challenges, government priority areas and societal need, focussing on our core research areas of Advanced Materials & Manufacture, Aerospace & Marine Technology, and Energy, Sustainability & Environment.
- Establish a distinctive culture of research partnership with industry, external research institutions and funding bodies to:
  - Develop and deliver single, multi- and inter-discipline research projects both nationally and internationally.
  - Fund new academic and research posts to establish/grow/support capability in core research areas.
  - Invest in high quality research infrastructure and equipment.
  - Increase the PGR population in key research and application areas.
  - Ensure clear and frequent communication with research partners and develop mechanisms for rapid transfer of research outcomes.

This strategy has delivered major improvements in our research environment. New research management structures have been developed, based around research Groups/Centres focused on our core research areas, accompanied by major increases in research income, staff and PhD students and investment in research infrastructure and equipment (Section d). The main enabler of these changes has been the development of new research collaborations at national and

international levels in line with our partnership-research policy (Section e).
These changes have resulted in a more vibrant research environment based on a sustainable economic model. This is evidenced by:

- More than doubling the research income from £4.9M in 2008-09 to £13.4M in 2012-13;
- 87% growth in EPSRC funding from £2.2M in 2008-09 to £4.2M in 2012-13;
- 7-fold increase in UK Central Government funding from £0.45M in 2008-09 to £3.28M in 2012-13 (a total of £6.3M in the REF period);
- 7-fold increase in UK Industry funding from £0.37M in 2008-09 to £2.64M in 2012-13 (a total of £8M in the REF period);
- 27 KTP programmes during the REF period, with KTP income growing by some 60% from £508k in 2008-09 to £814k in 2012-13

Achievements: Other indicators of the success of our strategy centre on the high calibre of staff and students within the UoA. Since 2008, 31 new academic staff with core research area expertise joined the UoA with significant increases in research staff and PGR populations (Section c). During the period, staff and researchers have gained considerable recognition from the community, including 17 elections to learned societies, 24 national or international honours, 11 competitively awarded fellowships, 42 prizes including medals and awards, and 22 other distinctions. The successes include: Sir Arthur Clarke Award 2012; International Astronautical Congress 2012 Gold medal; SET for Britain Gold medal 2012; EPSRC Doctoral Prize 2013; RINA William Froude Gold Medal 2012; Sustainable Achievement Award from the Royal Academy of Engineers 2011; UK Famelab finalist, Royal Institution 2012; 2 selected participants on inaugural Scottish Crucible 2009; EPSRC Grand Challenge Chemistry & Chemical Engineering 2008; IMechE Edwin Walker Prize 2011; IMechE Ludwig Mond Prize 2008; Franz Edelman Laureates Award 2012; Best of 2010 Articles Collection Europhysics Letters; UK representative on the European Federation of Chemical Engineering's Working Party on High Pressure Technology; Medal of Appreciation by the Institution of Engineering Designers 2013; Leverhulme Trust Research Fellowship in 2013.

Over the past five years the UoA has focussed its research activities into a number of new multi-discipline and inter-discipline research programmes, centres and facilities.

ADVANCED MATERIALS & MANUFACTURE:

- *Advanced Forming Research Centre*: holistic manufacturing-research projects bringing together computational mechanics, materials science, manufacturing technology, robotics, control, thermofluids, systems engineering & business processes (Section d).
- *Advanced Manufacturing Industrial Doctorate Centre (AMIDC)*: funded by EPSRC and industry, offers a 4 year research programme targeted at developing research concepts into full-scale industrial application, using combined academic and industrial experience. Recently added a 4-year EngD programme in Forging and Forming. Research outputs support UK Manufacturing, resolving and pushing boundaries of current manufacturing. A key theme is reinvigorating the Manufacturing economy and ensuring a strong future for the industry in the UK and beyond.
- A leading member of the University's *Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation (CMAC):* a team of 13 leading academics from 7 UK institutions, working with industry partners to accelerate the adoption of continuous manufacturing processes, systems and plants for the production of high-value chemical products to higher quality, at lower cost and improved sustainability. Associated with CMAC is a Doctoral Training Centre, with a vision to meet the demand for highly-skilled researchers to accelerate the adoption of continuous manufacturing for the production of high-value chemical particulate products.

AEROSPACE & MARINE TECHNOLOGY:

- *Advanced Space Concepts Laboratory*: interdisciplinary research projects including asteroid deflection and the development of multispectral canopy lidar technology. *Advanced Space Concepts Laboratory* hosts a range of interdisciplinary projects, including asteroid deflection research in conjunction with the University of Strathclyde Institute of Photonics (e.g. 14 partner €4M FP7 *StarDust* project and 4 partner €200k European Space Agency

SysNOVA projects, which combine space expertise in mission design with applied physics expertise in laser technology) and the £250k Centre for Earth Observation Instrumentation/Natural Environment Research Council project *An Early Mission Concept for a Spaceborne Multispectral Canopy Lidar*, with collaborators from the University of Edinburgh School of Geosciences and UK National Astronomy Technology Centre.

- *Centre for Future Air-Space Transportation Technology:* cross-department and inter-institution aerospace research, with activities ranging from fluid mechanics to aviation law. cFASST aims to perform the dedicated long-term planning and research required to create the space access and air transport systems of the future. cFASTT supports the space-access industry that has arisen since the demise of NASA's space shuttle, and works with Government and Industry to develop cost effective, efficient and reliable global transport and access to space. Projects include *Aerodynamic Shape Optimization for Hypersonic Vehicles*, with MBDA Missile systems, BAE Systems, Rolls Royce, Airbus (£100K); the €2.5M FP7 funded *Ablative Materials Modelling and Characterisation*, with DLR, Astrium, Von Karman Institute, Avio, CIRA, Amorim Cork Composites, Fluid Gravity Engineering, Austrian Institute of Technology, Osterreichisches Giesserei-Institut and European Space Agency.
- *Space Mechatronic Systems Technology Research Laboratory*: funded by the China Academy of Launch Vehicle Technology (CALT) (China's "NASA") and established in partnership with them in 2012. The Laboratory advances research in space related mechatronic technology and systems development. This is achieved by generating novel conceptual solutions for space exploitation which require high-level intelligence, fast response and efficiency. This prestigious resource is funded by the Chinese government for the next five years, with a minimum commitment of over £1M.
- *Strathclyde Marine Institute:* facilitates a wide range of multidisciplinary research projects involving engineering and science disciplines in offshore renewables, marine fuel cells, dynamic energy modelling, signal processing, ship design and manufacture, ballast water treatment and optical wave measurement.

ENERGY, SUSTAINABILITY & ENVIRONMENT:

- *Industrial Doctorate Centre in Offshore Renewable Energy (IDCORE)* is a partnership of the Universities of Edinburgh, Exeter and Strathclyde, the Scottish Association for Marine Science, and HR-Wallingford. IDCORE was set up by the Energy Technologies Institute (ETI) and is funded by the ETI and the EPSRC RCUK Energy programme.
- *Low-Carbon Power and Energy (LCPE*) is an industry-funded multi-disciplinary cross-Faculty research group within the new Strathclyde Technology Innovation Centre (TIC). LCPE research is divided into three themes, all focussed on offshore renewable energy: Asset Management, Networks and Offshore Foundations, Installation and Floating Systems. Out of nine projects currently funded in LCPE, researchers from Naval Architecture and Marine Engineering are leading four and active in one further project in collaboration with researchers from Strathclyde's Electronic and Electrical Engineering and Management Science departments.
- *Weir Advanced Research Centre*: a range of projects that combine fluid mechanics, structural integrity, materials science, design, manufacture and control to address challenges in pumping and flow control technology.

Strategy and plans: We intend to build upon the successes achieved during the REF period, using the capabilities that have been developed in the research Groups and Centres to focus on global challenges where innovative engineering solutions are required. Thus we plan to increase capacity in fundamental engineering research in sectors of international strategic importance, thereby raising the profile of the Strathclyde Engineering Research brand and boosting research income. We shall maximise the impact of our research by closely relating fundamental research and knowledge exchange, and by extending the scope and scale of collaborations with world leading research groups.

To achieve our vision, our strategic plan has been designed to continue to develop our infrastructure to provide our researchers with a world-class environment in which to work, to

maximise the impact of our research, and to enhance the sustainability and vitality of our research activity. Our strategic plan has 8 key objectives, to:

- Engage with government, industry and academic partners to identify and address key national and international research challenges.
- Develop single discipline, multi-discipline and inter-discipline research programmes across TRL levels 1 to 6, in which leading edge engineering science research is used to drive forward technology in a range of applications.
- Selectively recruit internationally leading research talent, thereby adding capacity through growth in the number of academic staff, contract researchers and PhD students.
- Provide a working environment that supports researcher career development, recognises achievement and rewards success.
- Invest in and maintain a high quality physical environment that provides researchers with the facilities and equipment required to support ambitious research programmes.
- Operate a sustainable business model to support research activities.
- Enable rapid transfer of research outcomes to business, the economy and society.
- Support the development of British and international standards and policies.

Plans already in place to achieve these objectives during the post-REF period include leading engagement in the University's Technology and Innovation Centre (TIC), an £89M "ground breaking initiative" (THE), devised to revolutionise the way academics and industry collaborate together in delivering impact through research and knowledge exchange, in particular in the sectors of Energy, Future Cities, Health and Manufacture. Also, we will create new centres of excellence in key research areas, e.g. a Nanomaterials Engineering Centre, to train the next generation of nanomaterials business leaders and to promote knowledge exchange. Our PGR population is set to continue to grow, with a target population of 274 by 2016. This will be achieved through expanding co-funding of studentships with industry and by establishing new Doctoral Centres. Strategic investment in new academic posts, aligned with key research areas, through initiatives such as the University's Chancellors Fellowship scheme, will see up to 50 new early-career researchers in post within AY2013-14. The UoA will benefit from investment in new/upgraded equipment/infrastructure, including a Ship Operations laboratory, and the £35M redevelopment of the James Weir building (to be completed in 2014) where three of the four departments are housed. A further increase in the number of industry-funded needs-based research projects will enhance our vitality and we will continue to promote a positive group climate, in line with the University's "One Strathclyde" philosophy. This is currently aided by Faculty-wide Research Seminars, Departmental level informal lunchtime Research Presentations, and the annual Faculty Research Presentation Day (a Faculty mini-conference which, being theme-based, promotes inter-departmental research crossover links).

c. People, including:

The UoA puts people, their development and support at the heart of all of its research activities and plans. Recruitment focusses upon attracting national and international leading researchers and providing a top class support environment.

Staffing strategy

Staff recruitment and support are key features of the UoA's research strategy; specifically the recruitment of internationally leading researchers and provision of a working environment that supports researcher career development, recognises achievement, and rewards success. 31 of the academic staff returned in UoA12 have been recruited into the core research areas identified in Section b since RAE2008:

- *Advanced Materials & Manufacture*: Dr N Acur Bakir, Dr M Amir, Dr I Boyle, Dr I Burns, Dr A Fletcher, Dr M Haw, Dr K Johnston; Dr M Jorge, Dr L Lue, Prof. X Luo, Dr S Patwardhan, Dr A Rentizelas, Dr S Thennadil, Dr Liu Yang; Dr Xhenyu Zhang.
- *Aerospace & Marine Technology*: Dr J Biggs, Dr E Boulougouris, Prof R Brown, Dr Kaklis, Dr Liu, Dr M Macdonald, Dr C Maddock, Dr E Minisci, Dr W Nicholls, Dr M Oliveira, Dr E Oterkus, Dr G Theotokatos, Dr M Vasile
- *Energy, Sustainability & Environment:* Dr H Chen, Dr I Lazakis, Dr N Srinil, Prof. S Tao

Seven of these staff members were recruited directly from universities in Denmark, Germany,

Greece, Portugal, and USA. New academic staff appointments were supported by start-up packages to fund PhD studentships and minor equipment purchases. Major investments in supporting laboratory and computing facilities are detailed in Section d.

The UoA departments co-invest with the Faculty to pump-prime research including Strategic Research Funding of up to £50k and Research "micro-grants" of £5k to support new initiatives. In addition, co-investments with the Faculty and University provide studentships to staff with priority given to new staff and early career researchers in core research areas.

Staff Development within the UoA is a key aspect of creating a vital working environment that allows researchers to fully realise their potential. The UoA provides a wide range of mechanisms to support and develop staff engaged in research throughout their careers. Through the University *Researcher Development Programme,* the UoA engages in a comprehensive range of opportunities for all researchers (including PGR students) to develop their personal, professional and career management skills. The University provides UoA staff with online bookable services including *My CPD*, *Mentoring@Strathclyde*, Induction events and 55 courses covering a wide range of research activities including presentation skills, publishing papers, writing-up a PhD thesis, developing research proposals, research ethics, entrepreneurship and knowledge exchange. These initiatives contributed to the University being shortlisted in the *Times Higher Education Awards* in 2011 and 2012 for 'Outstanding Support for Early Career Researchers'. Staff within the UoA have used their own training experiences to initiate, introduce and lead a formal 60 credit PGR training scheme, with Postgraduate Certificate, that has been cascaded throughout the University from the 1st October 2013.

Through the University's annual *Accountability and Development Review* process, all UoA staff engage in formal discussion with a senior colleague to review performance, set objectives for the coming year and define a learning and development plan. This is monitored throughout the year and formally reviewed at the following year's meeting. The University's commitment to staff development is reflected in the award of *Investors in People* status, re-confirmed in 2010.

The University's *Equality and Diversity Policy* is produced by the Equality and Diversity Strategy Committee, championed by Equality Officers. In 2011, the University was commended by *Athena Swan* for employment practices that further and support the careers of women and gained an institutional Bronze award. All UoA departments are currently in the process of applying for the *Athena Swan* silver award in April 2014. The University holds the *Double Tick* award, for commitments to employ, keep and develop the abilities of disabled staff. Each Department within the UoA has Disability and Ethics officers and Committees that monitor compliance with University policy.

The research staff career development procedures within the UoA fully align with the Principles of the *Concordat to Support the Career Development of Researchers*. Research staff joining the UoA participate in a formal *Research Induction Framework*. Each researcher is assigned an established academic or senior researcher who co-ordinates and monitors the induction programme, and a Mentor from their research group, who usually takes the role of *Reviewer* in the annual University *Accountability & Development Review* process. Following induction, the researcher can access an extensive range of career development support mechanisms through the *Researcher Development Programme*, with the *Mentoring @ Strathclyde* programme (which gives the opportunity to work with a second mentor from the wider research community) and the University Careers Service Career Development Reviews being especially useful. The University was presented the *HR Excellence in Research Award* by the EC in 2011 for its commitment to supporting personal, professional and career development of researchers.

New UoA Lecturer/Senior Lecturer appointments are assigned mentors depending on their specific experience/requirements: in some cases a single mentor, in other cases individual mentors for Teaching & Learning and Research. New staff are initially allocated low teaching and administrative loads to enable them to focus on establishing their research presence, and are given priority in the allocation of internally funded PhD studentships, to help them establish personal research teams. Early career UoA staff are required to complete PG Certificate courses in *Advanced Academic Studies* in both Academic Practice and Researcher Development. Researcher development includes modules in Building a Successful Research Career, Independent Enquiry, Public Engagement for Researchers and Research Bidding and Design. They may also participate in other *Researcher Development Programme* activities and engage

with the *Strathclyde Programme in Research and Leadership*, a tailored programme for Research Leaders, designed to support a broad range of career stages, developing and strengthening leadership in research and knowledge exchange across the University. The programme provides a range of seminars, courses and tools designed to directly support and align with the strategic Research, Knowledge Exchange, and collaborative international partnership ambitions of the University, leading to improved Research and Knowledge Exchange performance. All eligible new academic UoA staff apply for targeted ECR funding, (e.g. EPSRC First Grant, Challenging Engineering) with guidance and support from Mentors, the Research Director and other senior academics, who provide detailed advice and feedback during preparation of funding proposals. This has included provision of mock panels involving senior academic staff from other Faculties when appropriate.

We proactively encourage continuing career development for established staff within the UoA. Funds are allocated to pump-prime new research initiatives and develop research links with industry partners in the core research areas. Staff are fully supported by the UoA when applying for Research Fellowships that allow them to focus solely on research and will make suitable provision to cover teaching and administration duties during these periods. Examples of this include:

- A Royal Society of Edinburgh/Scottish Government Research Support Fellowship awarded to Dr I Trendafilova in 2010. This 1 year award allowed Dr Trendafilova to develop new research partnerships with the University of Bologna.
- An EPSRC International Collaboration Sabbatical award to Dr T Scanlon in 2011 enabled him to develop his international research profile and expertise in rarefied gas flows.
- A 1 year Research Fellowship from the Leverhulme Trust awarded to Dr M Haw in 2013 to develop use of optically enhanced flow to understand and control nucleation and growth.

Examples of the success of the Staff Development programme include:

Dr Iraklis Lazakis: After working in industry for 8 years, he enrolled as an MSc student in 2006-07 which he completed with distinction. In October 2007, he started a PhD with a University PhD Scholarship. He worked on various EU projects while studying towards his PhD degree, which he completed in July 2011 and was appointed as a lecturer in NAME on 1 September 2011. Since then he has been involved in teaching and research activities, and currently has around £1M worth of research projects funded by EU, industry and TIC. He is the co-ordinator of a €3M EU project 'INCASS', starting in October 2013.

Dr Winifred Ijomah: Having gained her PhD in Remanufacturing from the University of Plymouth in 2002, Dr Ijomah spent 4 years working as a Researcher at the universities of Sheffield Hallam and Bath. Appointed as a Lecturer at University of Strathclyde in 2007, Dr Ijomah is now a Senior Lecturer and editor-in-chief of the International "Journal of Remanufacture", sits on a BSI committee and is a Member of the Reuse Task Force of the UK Energy Minister's WEEE Advisory Group (WAB).

PGR Recruitment

We have focussed on four mechanisms for funding PGR studentships over the REF period:

- Attracting self or externally funded students, particularly from overseas, including students from Brazil, China, Kuwait, Nigeria, Pakistan and Turkey. Funding bodies include industrial and university sponsorships, the governments of China, Kuwait, Pakistan and Turkey, Marie Curie Research Training Fellowships and Nigerian Petroleum.
- Establishing Doctoral Training Centres. We host or are partners in four Doctoral Training Centres in strategically important research areas:
  - Advanced Manufacturing Industrial Doctorate Centre (host).
  - Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation Doctoral Training Centre (partner; host UoA3, University of Strathclyde).
  - Industrial Doctoral Training Centre for Offshore Renewable Energy (partner; host Edinburgh University).
  - Systems Engineering Doctorate Centre (partner; host Loughborough University).
- Co-investment with the Faculty, University and industry to sponsor research studentships with alternative schemes that specifically target projects aligned to core and Faculty/University strategic research areas, fundamental research, and exceptional students.

- Co-investment in industrially sponsored PhD studentships.
  - Partner companies include Babcock, BAE Systems, British Waterways, Carnival, GL-Noble Denton, Kilfrost Ltd., Lloyd's Register, National Nuclear Laboratory Ltd., Nigerian Petroleum, NPL, Pfizer, Qinetiq, Rolls-Royce, Scottish and Southern Energy, Shell, Spirit Aviation, Vaskutek, Weir Group, 2H Offshore Ltd,

PhD vacancies are advertised in standard HE recruitment web and print sites. Our staff also present information on PhD opportunities to students at international partner institutions. We run several programmes to encourage applications for PhD Scholarships from our own undergraduate students. Exemplars include:

- Informing final year BEng and MEng students directly through email/internal advertising of available scholarships.
- Presentations and research showcases for UG year groups on research careers and PhD opportunities.
- Participating in funded Summer Internship programmes, in which competitively selected year 3 and 4 students are introduced to research and research careers through working with a research group during the summer vacation.
- Integrating research study modules into the core curriculum.

An online application system is used to follow up applications and provide feedback to applicants. The University also runs pre-sessional English language programs for International students.

PGR Support and Monitoring

Our PGR population has increased significantly during the REF period, rising from 45 FTE in 2008-09 to 183 FTE in 2012-13, growth of over 300%. A range of activities and programmes have been implemented to ensure these students are fully supported in their studies and career development.

All new PGR students are assigned primary and secondary supervisors who have attended a specific training module or have an established track record in PGR supervision. All new students attend an annual *Faculty of Engineering Induction Day*, which allows them to meet with other students from their cohort and established PGR students involved in induction activities. Induction also covers specific practice topics including research techniques, use of the library and databases, good laboratory practice, research record keeping and health and safety issues. Individual provision is made for students unable to attend the induction day in their first few months of joining the University.

A robust formal procedure is in place to monitor and support student progress throughout the PGR period. Each student is required to complete an annual progress review. This involves completing an annual *Postgraduate Report* in which they detail their research progress, courses and conferences attended, papers published and any issues impacting on the progress of their research. Supervisors then provide written feedback on performance, and recommendations, and the report is passed on to a panel of academic staff convened by the Research Director, who independently monitor student progress. This is to provide progress feedback to the student and supervisor to help the student to complete their PhD on time, or to terminate the scholarship if appropriate. This includes advice with the research process as well as guidance on training and development.

All PGR students are encouraged to develop their research for presentation at national and international conferences and seminars. Student presentation skills development is facilitated by research presentation events within research groups and participation in the more formal Faculty annual Research Presentation Day event, attended by students, staff and external visitors from industry. First year students give a poster presentation and later year students a podium presentation. The presentations are assessed by a panel of academics and industrialists and prizes are awarded to all year groups. Students are also encouraged to enter national and international research competitions and many have been successful in these, for example the Sir Arthur Clarke Award 2012; International Astronautical Congress 2012 Gold medal; SET for Britain Gold medal 2012; and Best Paper Int. Conf. Manufacturing Research 2012.

PGR students are encouraged to become involved in a range of academic activities under the supervision of academic staff, including development of teaching skills in laboratory and tutorial

environments.

d. Income, infrastructure and facilities

On the 7th February 2012 a serious fire caused major damage to the James Weir (JW) building, where three of the departments contributing to UoA12 (CPE, DMEM and MAE) are based. This resulted in a near complete loss of the building's infrastructure and corresponding research facilities. Since then, all the effected UoA research active staff have been displaced from the building and were or are still dispersed over the campus. Given the demands for ensuring a high quality delivery of student experience, the event presented significant challenges for staff. On the other hand, it has also provided a considerable opportunity for the James Weir building to undergo a £35 million redevelopment, with significant investment being made in both facilities and infrastructure.

Research funding portfolio

By 2012-13, we had more than doubled our annual research income since 2008 to £13.4M. EU research funding grew by 60% and UK industry support grew 7 fold to £2.6M. The cumulative research funding for the REF period to 2013 is £41.5M, which includes £13.1M from RCUK, £12.1M from EU Government bodies, £6.3M from UK Central Government and £8.1M from UK Industry. Major investments in new facilities and upgrading existing facilities have been made since RAE2008. These investments align with the three key research areas identified in Section b, and with the strategic staffing strategy described in Section c.

Investment in New Facilities and Equipment

Advanced Forming Research Centre (AFRC): Collaboration between the University of Strathclyde, Scottish Enterprise, Scottish Government, Rolls-Royce, Boeing, Titanium Metals Corporation (TIMET), Aubert & Duval, and Barnes Aerospace led to the construction of a bespoke centre through investment of £35M for equipment and facilities. AFRC aims to develop forming and forging technologies to support the design and manufacture of components and structures for aircraft, cars, ships, medical devices, power generation and wind turbines. Research areas include: materials usage for economic and environmental benefit; new materials with improved metallurgical properties; new product designs demanding ever more accurate and repeatable formed components; and mass customisation requiring adaptable and flexible processes. AFRC undertakes programmes of core research in collaboration with its industrial members, as well as further R&D work for companies from around the globe. As of September 2013, the AFRC is engaged in collaborative projects with 20 industrial partners, who have collectively invested over £5M to deliver solutions to their business challenges. The researchers have engaged with worldwide industries and research communities (more than 40 companies including BAE Systems, Boeing, Bosch, Diad Group, Danfos, Gammastamp, Philips, Rolls-Royce). Projects include developing blue-sky products to lay the foundations of future forming and forging technology, as well as refining established industrial processes. Membership funding provides the budget to develop and implement the core research programme. Members' contributions are enhanced through applications to various UK and European R&D schemes. The AFRC is a founding partner in the High Value Manufacturing (HVM) Catapult.

Equipment includes: 105T **Jean Perrot Industries MANEO 105/30 Press Brake,** 500kN WF Maschinenbau 3-Roller Flow Forming/Spinning Machine, 2100T Schuler Multi-forge SP315 and **200T Superplastic Forming Press. The metrology & microscopy labs feature:** Quanta 250 FEG Scanning Electron Microscope with Electron Back-Scatter Diffraction, EDS and EDX spectroscopy, Alicona Infinite Focus G4 surface roughness scanning and micro-geometry measurement, GOM ATOS III Triple Scan with Photogrammetry, Mitutoyo Crysta Apex C12 contact measuring machine with Renishaw probe, Zwick micro-hardness tester, Land FTI-E 1000 thermal camera. The machines and instruments are operated by a team of skilled laboratory and workshop technicians who support the research staff.

Advanced Materials Research Laboratory (AMRL): The AMRL is equipped with £3M of materials characterisation and testing equipment, including: FE-SEM Hitachi SU-6600 with EDS, WDS & EBSD; W-SEM Hitachi S-3700 with EDS and environmental capability, Bruker D8 Advance Davinci XRD; GD-OES Horiba GD-Profiler 2; Netszch LFA 427, STA 449 F1 TGA DTA DSC, and DIL 402C TMA; Quantachrome Poremaster **Mercury Intrusion Porosimeter**; 4 Instron

servohydraulic/ electromechanical/ electrodynamic load frames with up to 250kN dynamic loading plus ancillary equipment. The AMRL is staffed by a director/business manager and 4 laboratory technicians. Projects include: *Towards Affordable, Closed-Loop Recyclable Future Low Carbon Vehicles* (TARF-LCV), EP/1038616/1 £4.2M, 8 UK University partners & 5 industry partners, Strathclyde award £475k. The facilities are also used extensively by the Weir Advanced Research Centre.

***EPSRC Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation (CMAC)*:** Members of the UoA play a leading role in this national centre which was established to accelerate the adoption of continuous processes for the improved production of high-value chemical products. With a funding portfolio of £60M, CMAC is physically located at Strathclyde with Bath, Cambridge, Edinburgh, Glasgow, Heriot-Watt and Loughborough universities as partners. EPSRC has supported CMAC with funding of £10M and more than £14M of additional funding has been provided by SFC and leading pharmaceutical companies, including GSK, Novartis and AstraZeneca. Recent further funding of £11.4M from HEFCE under the UK Research Partnership Investment Fund (UKRPIF) plus funding totalling £22.8M from industry and charity has enabled CMAC to become a formidable UK research hub. Part of the EPSRC sponsorship is an associated CDT that provides funding for 45 PhD students in this area. CMAC will move to the Technology and Innovation Centre in 2014. The UoA12 related equipment includes Bruker-Elvis Advance AXS D8 Capillary Diffractometer; Motic, B1 Series Digital Microscope; Wyatt DLS; Netzsch, 449C Jupiter DSC; Oscillated Baffled Reactor (NiTech, 1000 ml-Gl25 probe); Thermo Fisher, OXR Raman Microscope; Perkin Elmer, Autosystem Gas Chromatograph.

High Performance Computing (HPC): The initial £93k Faculty funded system comprised 100 2GHz AMD Opteron Cores, 4TB storage. A second £750k SFC/University funded system was added in 2010: 1000 Intel Xeon X5570 2.9 GHz cores, 2 128GB "fat" nodes, 130TB storage. UoA12 also benefits from the West of Scotland HPC Centre, ARCHIE West, funded in 2012 through a £1.6M EPSRC grant which provided: 3408 Intel Xeon X5650 2.66 cores, 8 512 GB "fat" nodes, 8 GPU servers, 150TB storage. HPC research is supported by a computing officer, who also facilitates/runs training programmes. UoA12 users include the James Weir Future Fluids Laboratory, Low Carbon Shipping-System Approach; FP7 AQUA (underwater noise emissions); FP7 FOUL-X-SPEL (antifouling marine coatings); SHELL funded Projects: Non-Equilibrium Fluid Dynamics for Micro/Nano Engineering Systems, and Multiscale Simulation of Micro and Nano Gas Flows.

Integrated Fuel Cell Laboratory: Established through £250k SFC/University funding, the laboratory houses two fully serviced/supported Fuel Cell Units - a 5kW low temperature hydrogen fuel cell, and a 5kW high temperature tubular solid oxide fuel cell. Example projects enabled by the facilities include: SUPERGEN: Delivery of sustainable hydrogen, £183k, EPSRC; SUPERGEN: Fuel cells powering greener future (Phase 2), £67k, EPSRC; Advancing Biogas Utilisation through Fuel Flexible SOFC, £306k, EPSRC.

Leonardo Centre: This is a £600k multi-disciplinary research centre (2009) in the James Weir building to support Departmental multi-disciplinary research activity. It provides working space and 'hot desks' for a wide range of staff, including researchers from Strathclyde's Institute of Operations Management and the AFRC.

In 2009 NAME purchased a sailing Yacht for teaching and research activities. The 10m yacht 'Catalina' is fitted with an engine and foldable propeller. It has been upgraded to make it suitable for full scale measurements for research activities. Initial investment was £50K and it was recently fitted with a £25K underwater/on-board noise measurement system. She is used in 2 current EU projects for underwater noise measurements and a study of long term performance of antifouling coatings (1 year cycle), FP7 EU project FOUL-X-SPEL

Other specialist facilities

Hydrodynamics Laboratory: This has the second largest UK towing tank; extensive capability in PIV flow measurement, force, pressure, and water surface instrumentation; and video and data acquisition & processing. REF period investment: installation of a multi-flap variable-water-depth absorbing wave-maker, new wave-absorbing beach, a novel digitally-controlled sub-carriage for study of structures subject to unsteady loading, and an optical motion capture system. Generates income of around £300k pa, for projects supported by EU, EPSRC, and the Shipping, Oil & Gas

and Marine Renewables industries. Example projects include: Energy Efficiency (Shell); Foul-X-Spel, and EPSRC/Marine Industry funded Low Carbon Shipping. A significant amount of the external income, circa £200k, goes towards annual upgrading and maintenance of the facilities, equipment and measurement systems.

Composite Materials Laboratory: Features thermal analysis, tensile testers (0.5kN & 2.5kN), autoclave (1m dia., 10bar, 600^{o}C), screw extruder and pelletiser, twin screw extruder, 25T injection moulder, vacuum assisted RTM, hot stage microscopy, FASEP fibre length measurement. The facility supported a range of activity including the Regenerated Composite Value Reinforcement (ReCoVeR) project, £461k.

Consultancies and professional services

During the REF period, consultancy income for UoA12 was £3.6M and grew by 87% from £705k in 2008-09 to £1,316k in 2011-12. Clients during the REF period included: MoD, BAE Systems, BAE Submarines, BP Exploration, British Council, CREW, Giltech, Highland Spring, M-Squared Lasers, Marine Ltd, Marine Biopolymers Ltd, Marlin Marine, Rathburn Chemicals Ltd, Rolls Royce, SAMS, Scotia Security Systems, Scottish Water, Strathclyde Links, Vascutek Ltd, Weir Engineering. The income generated was reinvested in research students and facilities in support of the UoA's strategy for growth.

e. Collaboration or contribution to the discipline or research base

Partnership working on single and multi-disciplinary projects is a key objective of our research strategy (Section b). The main drivers for this are to generate the funding required to make a significant contribution to the research base and to facilitate and enhance the transfer of research findings to the wider community.

Support for Research Collaboration

Collaborative research is strongly promoted and supported at all levels in the University and is underpinned by the activities of the Research and Knowledge Exchange Department which coordinates initiatives to stimulate internal collaborative working (e.g. through Bridging the Gap funding) and facilitates external engagement by providing a supportive service in all matters pertaining to intellectual property, patents, commercialisation and legality of contracts. The UoA has also benefited from faculty co-funding of collaborative activity including pump-priming research and visits to prospective partners. Within the university, collaborative projects have been established with colleagues in the Business School, Science and other Engineering departments on topics including: production and purification of Escherichia coli alkaline phosphatase for use in projects such as enzyme driven colloidal motion and enzyme mediated self-assembly; continuous synthesis of advanced nanoporous materials for applications in energy H_2 storage and industrial catalysis; and drug delivery applications of bio-inspired silica. We have especially valued interactions with the Business Engagement Group, which adopts a business-oriented approach to technology and innovation management, covering risk, optimisation, product design and production processes.

Exemplars of Research Collaboration

The Technology and Innovation Centre (TIC) provides the UoA with opportunities to expand industry engagement and multi-disciplinary collaboration through projects in the four main themes of Low Carbon Power and Energy (LCPE), Future Cities, Health, and Manufacturing. We have already established funded TIC-related projects in collaboration with colleagues in Electronic and Electrical Engineering and Management Science at Strathclyde, and Industry partners SSE, Scottish Power and Technip. The industrial partners will provide £1M pa in research funding over the next 5 years for projects based on their strategic needs.

The **Advanced Forming Research Centre (AFRC)** mentioned previously in Section d, undertakes an industry focused programme funded by Tier 1 partners Rolls-Royce, Boeing, TIMET, Aubert & Duval and Barnes Aerospace. Further companies provide lesser direct funding to the Centre as Tier 2 partners. The research agenda for the Centre is set by the Technical Board which includes representatives of all Tier 1 and Tier 2 partners, and an academic representative from the Glasgow Research Partnership in Engineering. Staff from Tier 1 partners are permanently located at AFRC and interact with our Strathclyde staff. The AFRC is a member of GlobalNet, a group of Boeing-engaged international research centres.

The **Weir Advanced Research Centre** (**WARC**) was established by Weir Group Plc. as a global

research hub in 2011 following a pilot collaborative R&D project between Weir SPM, Texas, USA and UoA12 staff. 12 of our academics are engaged in the current research programme, supported by 2 Research Associates and 6 PhD students. The WARC Board is Chaired by the Weir Group Director of Operations Support & Development. Board members are the 3 Divisional VPs Engineering from Weir Oil & Gas, Weir Minerals and Weir Power & Industrial, the Weir Group WARC Engineering Director, Strathclyde staff and the University Special Operations Director. The Centre's programme is designed to meet research needs specified by the three Weir Group divisions. Projects span the TRL range 1 to 6, and each has a specific Champion from the Weir Group working closely with the research team.

The **Space Mechatronic Systems Technology** (**SMeSTech**) is a collaborative programme between UoA12 staff and the China Academy of Launch Vehicle Technology, CALT, co-funded by the Chinese Government with a minimum commitment of over £200k pa. CALT agreed to second two senior engineers from the company to work on the projects within the laboratory at Strathclyde.

Collaborative projects

Exemplars of interdisciplinary research that are not related to specific industry-focused centres include: the RCUK funded programme in Low Carbon Shipping, combining technical modelling of ship systems with logistics, economics, environmental impact and forecasting; and the ETI/EPSRC-funded Industrial Doctoral Centre in Offshore Renewable Energy established with Edinburgh and Exeter Universities, covering technical, economic and environmental aspects of offshore renewable energy.

During the period 2008-12, UoA12 researchers have participated in over forty EU Framework projects with a total value of £12M. Also, twenty-five multi-partner EPSRC funded projects were won worth over £20M. The research topics funded through the EPSRC grants included:

Low-Carbon Shipping; Shipping in Challenging Climates; An O_2 electrode for rechargeable lithium battery; Advancing biogas utilisation through fuel flexible SOFC; Crossing boundaries in energy storage; Feasibility for new gas separation process; Customisation of cosmetic covers for artificial limbs; Design of polymer-clay nano-composites; Managing the manage process; and Low-carbon Shipping. Other significant projects on the manufacture of ultra-fine grained materials, and new gene delivery materials to produce bioplastics and biofuels, were funded by Carpenter Technology Corp. and the Japanese Government, respectively.

Collaborative leadership

We are highly active in the International Towing Tank Conference, a key international body that sets standards for hydrodynamic testing, and the International Ship Structures Committee. Staff have also contributed over many years to important international regulatory bodies including the International Maritime Organisation, and classification societies including Lloyds Register of Shipping, American Bureau of Shipping, and Det Norske Veritas.

Other examples of UoA12 staff leadership include: champion for 'Artificial life' at EPSRC Grand Challenge Chemistry & Chemical Engineering meeting; member of the CCP5 Executive Committee; Member, International Advisory Board, Institute for Cell and Materials Science, Kyoto, Japan; RAS Space Group Committee; Scottish Government Aerospace, Marine and Defence Strategy Consultation Team; Advanced Investigator European Research Council; Engineering Coordinator of the MSP Science Information Service, National Space Technology Strategy Group; International Electrical Committee TC114 for the development of standards for marine renewables; International Energy Agency's Ocean Energy Systems Implementing Agreement Annex on the development of standards for marine renewables; European Science Foundation International Assessor for Eurcorres grants on Nanotribology; Austrian Science Foundation International Assessor for National Tribology Centre; Space Power Committee of the International Astronautical Federation; ESA/DLR Solar Sail Working Group.

Collaborative visits

Cross-fertilisation of research ideas and partnering has been strengthened through hosting visiting international scholars, including for example Prof E Manoach, (Institute of Mechanics & Biomechanics, Sofia), Prof W Ostachovicz and A Zak (Polish Academy of Sciences), Dr H Yu (Beijing, China), Prof N Mei (Ocean University, China), Dr Y Wei (Zhijiang, China), Prof. L Doctors (USW, Australia), Prof. M Vasconellos (COPPE/UFRJ, Brazil), Dr I Yalcin (ITU, Turkey) and Prof. Tomoki (Nihon, Japan). These visits have led to joint publications as well as research projects.

Several of our academics have also been visiting scholars at international universities during the REF period, including engagements in China, France, Japan and Taiwan.

Collaborative community exemplars (2008-2012)

Over the REF period staff have made considerable contributions to the international community. *Journals and Editorial Boards*: 5 journal editorships – Prof. **Antony**, Ed. International Journal of Lean Six Sigma; Prof. **Duffy**, Ed. Journal of Engineering Design; Dr **Ijomah** Ed. Journal of Remanufacturing; Prof. **Incecik** Ed. Ocean Engineering; Prof. **Qin** Ed. Journal of Manufacturing Review. There were a further 82 instances of staff engaging in editorial activity, including Dr **Patwardhan**, Ass. Ed, Silicon; Prof. J **Corney** Ass. Ed. ASME/ACM Journal of Computing and Information Science in Engineering; Prof **Mackenzie**, Ass. Ed. ASME Journal of Pressure Vessel Technology; Dr **Trendafilova**, Subject Ed. Journal of Sound and Vibration; Ed. Brd. Dr **Bakir**, Ed. of Journal of Product Innovation Management; and guest editorships from Dr **Macdonald**, Guest Ed. AIAA Journal of Guidance, Control and Dynamics 2009; Prof. **Schaschke,** Guest Ed. Int. Journal of Food Science and Processes; Prof. **Stack**, Guest Ed. Tribology International, 2010.
Conferences: Staff were involved in the organisation of 153 major conferences, including Dr **Ijomah** who initiated and chaired the first international conference on Remanufacturing (ICoR); **Dr Lue**, Thermodynamics 2011 and **Prof. Duffy**, Chair 2nd International Conference on Design Creativity 2012; Prof. **Vassalos**, organiser and chairman of IMDC 2012 (11th International Marine Design Conference); and Prof. **Turan**, Organiser and Chairman of HPAS 2010 (4th International Conference on Human Performance at Sea); and 33 special symposia. Staff also participated in 577 conferences, delivering keynote presentations or plenary lectures on 144 occasions, including: **Dr Johnstone**'s keynote presentation at the European Wave and Tidal Energy Conference, Aalborg 2013, **Dr Qin**'s address at the 12th AMFT (Plasticity Engineering Conference) in Chongqing, August 2011, and **Dr Luo**'s plenary lecture at the 1st World Congress of Nanoscience & Technology.

Other indicators of community contributions include: 42 memberships of advisory panels to industry, government or NGOs, including **Prof. Bititci**'s membership of the Scottish Manufacturing Advisory Board, and **Prof. Vassalos**'s membership of the Council of Safety Committee of the Royal Institution of Naval Architects; 17 appointments or secondments with industry or commerce, for example **Dr Boyle** was appointed Research Fellow then Lecturer as part of a strategic partnership between the University and BAE Systems in 2012, and **Dr Srinil** participated in an industrial placement at Maersk Oil via the International Foundation for Science award; membership of 57 public or government advisory or policy groups, for example **Dr Jorge**'s membership of the Steering Committee for ICoRSA, and **Prof. Incecik**, Member of the Research Strategy Planning Group of the EU-FP7 Waterborne Technology Programme; hosted 104 external, non-academic visitors; participated in 170 workshops/networks with non-academic organisations; contributed to the work of 122 national or international committees or working groups, for example **Dr Mulheran**, Elected Committee Member, Institute of Physics Nanoscale Physics and Technology Group, and Prof. **Day**, Chairman of Int. Towing Tank Conf.'s (ITTC) specialist committee on 'Hydrodynamic Testing of Marine Renewable Energy Devices'; membership of 45 external research organisations, including **Prof. Duffy**, past Vice-President, President, Advisory Board member and one of 13 Honorary Fellows of the international Design Society, and **Prof. Vassalos**, member of the EPSRC Marine Technology College; and research and teaching at 124 external organisations.