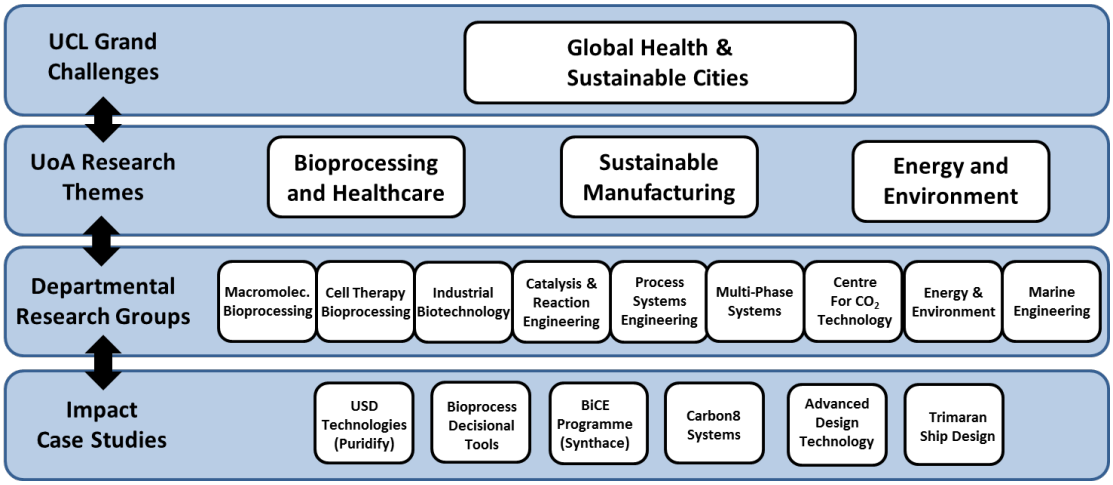
Institution: University College London

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

a. Overview

This submission comprises the departments of Biochemical (**BE**), Chemical (**CE**) and Mechanical (**ME**) Engineering. It represents 54.16 FTE total; 19 from BE, 21.76 from CE and 13.4 from ME. UoA staff help define and make internationally leading contributions to the institutional research priorities described in the **UCL Grand Challenges of Global Health and Sustainable Cities** (www.ucl.ac.uk/grand-challenges/). Contributions are made within three overarching Research Themes representing Faculty priorities: Bioprocessing and Healthcare, Sustainable Manufacturing, and Energy and Environment. Nine Research Groups contribute to these Themes as shown below. Staff are supported in delivery of the **UCL Enterprise Strategy** (www.ucl.ac.uk/enterprise/) (see REF3a) and significant impact has been achieved in relevant industry sectors (see REF 3b).



The Research Groups operate within the interdisciplinary **UCL Faculty of Engineering Science** (www.engineering.ucl.ac.uk/) and are leading proponents of the Faculty mission to **'Change the World'**. Under strategic leadership of the Dean (Prof A. Finkelstein, FREng) the Faculty is currently second in the UK, based on EPSRC grant income, and is the second most impactful engineering Faculty in Europe based on citations (Thomson Reuters, 2010). Over the last 3 years there have been 70% increases in Faculty research income and researchers and UoA 12 staff (**Simons, Fraga**) have led on creation of **UCL Australia** (www.ucl.ac.uk/australia). New departments of Management Science and Innovation (MSI) and Science, Technology, Engineering and Public Policy (STEaPP) support UoA staff in delivering the enterprise and policy aspects of their research.

The Faculty has invested heavily in UoA 12 with 13 new staff since 2011 including new, externally recruited, Heads in CE (**Coppens**, 2012) and ME (2013). The environment is young and dynamic with 13% of staff classified as Early Career Researchers. Research expenditure over the REF period stands at £25.6M while current research income totals £61.4M. Senior staff lead a number of **internationally leading EPSRC-funded activities** including: the £5.3M Centre for Innovative Manufacturing (CfIM) in Emergent Macromolecular Therapies (Director, **Titchener-Hooker**); the Centre for Process Systems Engineering (with Imperial College, Deputy Director, **Bogle**); the £5M Centre for Nature Inspired Engineering (Director, **Coppens**) and a £3.5M Low Carbon Shipping programme (Director, **Bucknall**). These Centres foster collaborative research across the UoA and UCL as evidenced by co-authored REF outputs. Staff lead two **EPSRC Doctoral Training Centres** (DTC), the £6.5M industrial DTC in Bioprocess Engineering Leadership (Director, **Lye**) and the £2.5M DTC in Emergent Macromolecular Therapies (Director**, Dalby**), and **co-ordinate three FP7 projects**. Strategic research contributions from the unit were recognised by award of the **Queen's Anniversary Prize in Higher Education** (2013). Staff and researchers are therefore part of a vibrant and growing research environment with strong institutional support and leadership.

b. Research strategy

The research objectives from RAE2008 have all been met as described in the box below. This is followed by a description of individual Research Group achievements and their priorities over the

next 5 years (lead academics underlined). Finally we present the broader strategic UoA priorities.

• In **BE** (UoA26 in RAE2008) the main objective was to establish '*automated micro-biochemical engineering methods*' with '*direct linkage to process modelling and bioprocess design*'. This was achieved and the outputs (see REF2) underpinned award of the **EPSRC Centre for Innovative Manufacturing** in 2011. A further goal was to apply these to the emerging area of '*human cells for therapy*'. Growth of the Cell Therapy Bioprocessing group (see below) indicates our success.

• In **CE** (UoA26 in RAE2008) the strategic goal was to '*expand the scope and reach*' of the Centre for CO_2 Technology (CCO2T). This was achieved as evidenced by establishment of **UCL Energy Technologies** in 2013 (www.ucl.ac.uk/energy-tech), a cross-UCL activity involving nine UCL departments across four faculties (see below). Further CE goals were defined at Research Group level and delivery of these is described in the following Research Group descriptions.

• In **ME** (UoA28 in RAE2008) the strategic goals were to '*increase engagement with life/clinical sciences*', '*bridge bio-medicine and engineering at UCL*' and establish '*world-class research facilities*' in this area. These were achieved as evidenced by creation of the **UCL Institute of Biomedical Engineering (IBME)** in 2012 (www.ibme.ucl.ac.uk/). The IBME is included in the UCL REF2014 UoA15 submission, along with 13 ME staff, and so is not described further here.

1. Macromolecular Bioprocessing (Baganz, Bracewell, Dalby, Farid, Hoare, Keshavarz-Moore, Lye, Micheletti, Mukhopadhyay, Nesbeth, Szita, Simaria, Titchener-Hooker, Velayudhan, Ward, Zhou) (Web: www.ucl.ac.uk/biochemeng/industry/epsrccentre). The focus is on achieving rapid translation of novel biopharmaceuticals into commercial products. Research within the **£9M EPSRC Innovative Manufacturing Research Centre (IMRC) in Bioprocessing** (EP/E001599/1), with over 150 publications during the REF assessment period, underpinned these studies. Achievements to which **all the above staff** have contributed, include:

- Creation of industrially validated Ultra Scale-Down (USD) technologies for rapid bioprocess characterisation and invention of novel cost-effective and scalable purification technologies leading to spin-out company formation i.e. Puridify Ltd (see REF 3b USD Impact Case Study).
- Creation of automated microwell methods to speed process design and scale-up (see REF2).
- Establishment of novel algorithms and software, integrating process and business models, to enhance facility design and operation (see REF3b Decisional Tools Impact Case Study).
- Integration of USD approaches with advanced engineering of bacterial (with Warwick University) and mammalian (with Kent University) expression systems through £3.7M of joint BBSRC-EPSRC Bioprocessing Research Industry Club (BRIC) awards.

Future goals align with the mission of the new EPSRC CfIM in Emergent Macromolecular Therapies (EP/1033270) i.e. to establish a holistic approach linking discovery to manufacture with greater certainty of manufacturing outcomes and at lower cost to the NHS. Strong progress is being made particularly in addressing manufacture of next generation vaccines (FP7, GA602437).

2. Cell Therapy Bioprocessing (Farid, Hoare, Lye, Mason, Simaria, Szita, Veraitch, Wall) (Web: www.ucl.ac.uk/biochemeng/industry/regenmed). Formed in 2006, the focus is to accelerate the safe, clinical efficacious and cost effective translation of cell therapies into commercial products. Fundamental bioprocess research in collaboration with clinical groups has supported the development and clinical application of various cell therapies. Achievements include:

- Design of novel bioreactor and bioprocessing technologies to maintain the mechanical integrity of decellularized scaffolds for tissue-engineered airways (**Wall, Mason**). These cGMP-compatible approaches have successfully treated NHS patients in experimental surgery.
- Creation of USD (**Hoare**) and microfluidic (**Szita**) methods for early stage bioprocess development e.g. to quantify shear effects on the quality of cell-based cancer vaccines.
- Study and optimisation of the impact of oxygen tension on stem cell culture (**Mason, Veraitch, Wall, Lye**) e.g. for corneal regeneration. These approaches are now routinely incorporated into the cGMP manufacture of corneal cell therapies at Moorfield's Eye Hospital.

Future research priorities will build upon Decisional Tools research (**Farid, Simaria**) within the Centre for Innovative Manufacturing (see above) to improve the manufacturing efficiency, health technology assessment and clinical adoption of new cellular and gene therapies. Grant income

continues to grow with new awards in 2013 addressing cell therapy scale-up (BB/K011154, **Wall**) and economics (FP7, 'BIOtrachea', €4M; MRC Biomedical Catalyst 'RegenVox, £2.8M, **Mason**).

3. Industrial Biotechnology (Baganz, Dalby, Lye, Micheletti, Nesbeth, Szita, Ward) (Web: www.ucl.ac.uk/biochemeng/industry/bice). This multidisciplinary group focuses on biocatalysis in chemical and pharmaceutical manufacturing. It was established in 2005 following a major EPSRC award (GR/S62505) and has produced over 80 journal publications during the REF period. Fundamental research aims to create new industrial biocatalysts and novel technologies to speed bioprocess development. Industrial uptake and commercialisation of outputs is described in the BiCE Impact Case Study (REF3b). Specific research achievements since 2008 are listed below.

- Cloning and molecular engineering of novel enzymes with improved stability and enhanced enantiospecificity for use in industrial organic synthesis (**Ward, Dalby**).
- Design and engineering of whole cell biocatalysts for efficient, multi-step synthesis of chiral chemicals from renewable resources (**Baganz, Nesbeth, Ward**).
- Establishment of novel synthetic routes for chiral amino alcohol synthesis (**Dalby, Micheletti, Ward**) in collaboration with Prof Helen Hailes (UCL Chemistry).
- Creation of automated microwell methodologies and miniature bioreactor technologies to speed biocatalytic process design and scale-up (**Baganz, Lye, Micheletti**).

Future research will focus on increasing the efficiency of renewable resource utilisation. This will demand integration of emerging technologies in Synthetic Biology (**Nesbeth**) and continuous flow enzyme reactors (**Szita**) within our overall whole bioprocess design philosophy. Progress is being made with new BBSRC (£1.1M, BB/L000997) and EPSRC (£2M, EP/K014897) grants in 2013.

4. Catalysis and Chemical Reaction Engineering (Angeli, Brett, Coppens, Gavriilidis, Kuhn, Mazzei, Manos, Shearing, Stamatakis, Tang) (Web: www.ucl.ac.uk/chemeng/research/catalysis-reaction). Catalysis and Chemical Reaction Engineering address core challenges in environment, energy and manufacturing. To this end, the group deploys its expertise in efficient and economic utilisation of chemical transformations. The catalytic materials and reactor technologies developed by the group find applications from renewable energy to sustainable, green manufacturing in the chemical industry. Since 2008 achievements include:

- The group's expertise on microreactor technology and microfluidics research has been internationally recognised, as demonstrated by a strong publication record (see REF2) ever-expanding collaborations and EPSRC (e.g. EP/I031480/1) and industrial grants (**Gavriilidis**).
- Research is expanding in new catalytic technology areas (e.g. for water treatment) (**Tang**).
- A strategically important initiative is the Electrochemical Innovation Laboratory which has hydrogen safe laboratories capable of fuel cell and electrolyser research (**Brett**).
- Involvement with users increased via Impact and CASE awards (e.g. NPL, AFC Energy, Tata Steel), and the newly formed UK Catalysis Hub (**Brett, Coppens, Gavriilidis**).

Future research will deliver innovative and green solutions in energy applications and sustainable chemical manufacturing with a special focus on materials/nanoparticle synthesis. To support this, we will expand our analytical and materials characterisation infrastructure, through £1M UCL Faculty support. Progress is also being made with new EPSRC grants (e.g. £1M, EP/L003279/1).

5. Product & Process Systems Engineering (Bogle, Dua, Fraga, Papageorgiou, Sorensen, Stamatakis) (Web: www.ucl.ac.uk/chemeng/research/product-process). The group researches modelling and optimisation methodologies for decision making for complex systems with a focus on innovative manufacturing, energy systems, healthcare, materials and water. PPSE is a partner in the Centre for Process Systems Engineering (CPSE), a joint venture with Imperial College London, supported by a consortium of 9 companies facilitating industry collaboration and technology transfer. The strategic aim is to develop methodologies for challenging complex process systems engineering problems. Since 2008, specific achievements include:

- Research in innovative manufacturing was expanded through involvement in the EPSRC Centre for Innovative Manufacturing in Emergent Macromolecular Therapies (see above).
- Research on novel materials for CO_2 capture and use (with UCL Chemistry, Thomas Young Centre) and sustainability (Institute of Sustainable Resources, UCL Australia) was established.
- A complex model of glucose regulation in the human liver system in collaboration with UCL Medical and Physical Science Departments was developed.

The PPSE group will strengthen competences for multi-scale modelling methodologies and extend

the range of problem domains, particularly in innovative manufacturing, energy systems, water management, design of novel materials, and modelling physiological systems for design of better healthcare. Methodological developments will focus of the systematic handling of risk and uncertainty and expanding the use of data analytics to different application domains.

6. Multi-Phase Systems (Angeli, Jones, Kuhn, Lee, Lettieri, Mahgerefteh, Mazzei, Shearing, Simons, Striolo, Yazaydin) (Web: www.ucl.ac.uk/chemeng/research/multiphase-systems). The group focusses on experimental investigations, modelling and design of multiphase processes across length scales, involving novel imaging (X-Ray, muon tomography), flow diagnostics (laser based systems), analytical techniques (spectroscopy) and computational fluid dynamics (CFD) approaches. Our research tackles challenges on sustainable energy, transport of hydrocarbon mixtures and of CO_2, fluidization processes for energy from waste and advanced manufacturing of chemicals and materials. Since 2008 specific achievements include:

- New models for safe and efficient multiphase transportation in pipelines of oil (£1.6M; Programme Grant EP/K003976, **Angeli**) and CO_2 (EP/G061955, National Grid, **Mahgerefteh**).
- Establishment of world leading X-ray imaging facilities for non-destructive characterization of a variety of materials and fluid-particle systems from nm-mm length scales (**Lettieri, Shearing**).
- Unique studies in micro/millilitre scale systems for intensification of two-phase processes and controllable and reproducible nano and micro particle synthesis (**Kuhn, Mazzei, Angeli**).

The Group's future vision is to exploit our strong science base, unique experimental infrastructure, particularly on imaging, and multiscale modelling capabilities. We will advance research on scalable manufacturing, materials, and sustainable, low carbon energy including reprocessing of nuclear spent fuel, and CO_2 mitigation, spanning across discipline interfaces (e.g. chemistry, maths, geo-physics) while expanding our portfolio of industrial collaborations (e.g. Shell).

7. Centre for CO_2 Technology (Brett, Fraga, Lettieri, Mahgerefteh, Simons, Shearing, Tang) (Web: www.ucl.ac.uk/centre-for-co2-technology). The CCO2T leads research on developing breakthrough technologies for the large scale reduction of CO_2 emissions (e.g. alternative, low carbon, energy sources; nuclear energy; CO_2 conversion), safe and economical capture, transportation and storage (CCS) of CO_2 as well as transformation of fossil fuels to low-carbon energy systems. Since 2008, specific achievements include:

- Commercialisation of mineral carbonation as a waste treatment / CO_2 capture and storage technique via the spin-out of Carbon8 Systems (see REF 3b Impact Case Study) (**Simons**).
- Establishment of a pioneering 'open innovation' model leading to company spin-outs (e.g. Amalyst Ltd. commercialising electrocatalysts for fuel cells) and £2.95M (EP/J021199/1) funding with UCL Chemistry in Grid Scale Energy Storage (**Brett, Shearing**).
- Life-Cycle Analysis application to distributed/centralized energy generation systems (**Lettieri**).
- Research on CO_2 pipeline safety and CCS techno-economic assessment (FP7, CO2PipeHaz, GA24136, €2.7M and CO2QUEST, GA309102, €4M) (coordinator **Mahgerefteh**).

Future research will address: sustainable and secure energy supply based on low carbon renewable sources and clean coal technologies; studies on fuel cells, energy storage and renewable energy (building on successes in solar energy research); zero emission and sustainable chemicals processing, particularly through artificial photosynthesis of CO_2; nuclear energy, waste disposal and spent fuel reprocessing, building on the REFINE consortium (£1.1M, EP/J000779/1).

8. Energy and Environment (Aleiferis, Balachandran, Eames, Ladommatos, Zangeneh, Ducci, Balabani, Luo) (web: www.ucl.ac.uk/mecheng/research/energy-and-the-environment). The group has matched strengths in the experimental study of combustion and new fuel technologies (**Aleiferis**, **Ladommatos**, **Balachandran**) and the application of High Performance Computing (HPC) to model these processes (**Luo, Zangeneh**). Specific achievements include:

- Establishment of the **Jaguar Centre of Excellence** in 2013. This is supported by a consortium of automotive (e.g. Ford, Jaguar, MAHLE Powertrain) and fuel (e.g. BP, Shell) companies. Pioneering research on combustion of future sustainable fuels derived from bio-mass and hydrogen combustion in an optically accessible engine and in gas turbine engines is funded by EPSRC (e.g. EP/C520211/1), BP Oil, Lotus Engineering, and Delphi.
- Development of computational design methods based on 3D inverse design and multi-objective and multi-disciplinary optimization of turbomachinery blades (**Zangeneh**). These are licensed to IHI, KHI, and Kubota in Japan and Avio Group and Voith Turbo in Europe through our spin

out company ADT (see REF3b Impact Case Study) and patented internationally.
Future plans focus on enhancing HPC capabilities and the study of novel fuels and combustion processes in spark-ignition engines through the Jaguar Centre. The scope of the group will also expand to address separation technologies for algae biofuel manufacture (**Balabani**) and to establish optimised mixing protocols for chemical and biochemical reactors (**Ducci**).

9. Marine Engineering (Andrews, Bucknall, Fromme, Greig, Tan, Wu) (web: http://www.ucl.ac.uk/mecheng/research/marine). A distinct strength is 40 years funding from the Ministry of Defence (MoD), £350k pa, that underpinned research on the world's first ocean-going trimaran ships (see REF 3b Impact Case Study). Research achievements include:

- Reduction of the CO_2 footprint of the Marine sector through a £3.5M EPSRC funded (EP/K039253/1) activity on Low Carbon Shipping (**Bucknall**, **Greig**). This is complemented by research on lightweight sandwich systems for combined blast and impact amelioration in ships funded by EPSRC (EP/I028811/1), MoD and Lloyd's Register (**Tan**) and new methods for the Structural Health Monitoring (SHM) of ships and offshore structures using guided ultrasonic waves funded by EPSRC (EP/D065011/1) and Airbus (**Fromme**).
- Establishment of a joint research centre on deep water challenges (£1.25M Lloyd's Register, **Wu**), involving UCL, Shanghai Jiaotong University (SJTU) and Harbin Engineering University (HEU), which builds on UCL's expertise and previous role in North Sea development.
- Pioneering studies on Naval Ship Layout. This builds on UCL's architecturally centred Computer Aided Ship Design innovations and is supported by a $1.5M Office of Naval Research project, NICOP (**Andrews**) in collaboration with Michigan and TU Delft.

Future research will focus on Engineering in Extreme Marine Environments to account for the influence of (extreme) temperature, pressure, loading and chemistry on complex structures. This will particularly involve investigation into sustainable use of resources and energy in/below the sea.

STRATEGIC RESEARCH PRIORITIES. In addition to individual Research Group goals, the UoA has three strategic, cross-disciplinary research priorities that will be delivered in the next 5 years:

• We will **establish UCL as the UK focus for Nature Inspired Engineering** to compete with the leading US centres. Here we will discover fundamental mechanisms behind desirable traits in natural systems, such as scalability, robustness and efficiency, and use this insight to guide the design and synthesis of engineered systems that have similar properties. This builds on 2013 funding to establish the **EPSRC 'Frontier Engineering' Centre for Nature Inspired Engineering** (EP/K038656) directed by **Coppens** with research leads in each of the three UoA12 departments: **Bracewell**, **Gavriilidis** and **Miodownik** (in UoA 15). The Centre already has support from 17 company partners including ExxonMobil, Johnson Matthey, Air Products and Shell.

• We will leverage our leadership of the cross-UCL SYNBION network (BB/F018703/,1 **Ward**) (www.ucl.ac.uk/synbion/network) to **establish UCL as the international focus for research integrating advances in Synthetic Biology with future bioprocesing technologies** in the chemical, (bio)pharmaceutical and cell therapy sectors. We have already won underpinning grants on engineering novel biopharmaceutical expression systems (e.g. BB/K011243, **Keshavarz-Moore**), advanced biocatalysts (ERA-IB.12.026, **Micheletti**) and on microfluidic technologies for continuous biomanufacturing (BB/L000997, **Szita**). Industrial impact is facilitated £3M HEFCE Catalyst Fund (**Lye**) and IKC in Synthetic Biology (EP/L011573, **Ward**) awards in 2013.

• We will build on successful collaborations established within UCL Energy Technologies, a virtual cross-UCL domain with a mission to enhance research and innovation on energy systems (an RAE2008 objective), to **create a Centre of Excellence in Future Fuels and Technologies for Transport**. Led by ME (**Aleiferis, Bucknall**) this will bring together expertise in fuels, combustion, propulsion design and transport systems to establish a world-class, multi-disciplinary research activity involving staff from seven UCL departments (including BE and CE) and the UCL Energy Institute (www.bartlett.ucl.ac.uk/energy) addressing all transport sectors (road, rail, sea and air).

c. People

1. Staffing Strategy and Staff Development: Of paramount importance to the continued success of UCL is the recruitment of senior staff who are internationally recognised leaders and of junior staff who will become leaders in their field. 5-year staffing plans are developed by departments, in

consultation with Research Group leads, and reviewed annually at Faculty level with input from the Dean. Positions are advertised internationally and for senior appointments, head-hunters are engaged. UCL support for the UoA has led to 6 senior and 10 junior appointments during the REF assessment period spread as follows: 2008 (1); 2009 (2); 2011 (3); 2012 (4); 2013 (6). The contributions of new staff and our **Staffing and Development Strategies** are summarised below.

• **Senior appointments**: At professorial level **Coppens** was appointed as CE HoD in 2012. Coming from RPI in the US he brings expertise on various aspects of catalysis and reaction engineering with a particular focus on nature-inspired designs. Ventikos, appointed as ME HoD in 2013, comes from Oxford University and brings strengths in fluidics and biocomplexity. He is returned in UoA15 given the Biomedical focus of his research. **Striolo** (2013) coming from the US, brings molecular thermodynamics expertise. **Luo** (2013) is an expert in CFD, and complements the strength in experimental activities in fuels and combustion while **Ward** (2012) was brought in to lead activities in industrial synthetic biology. At Reader level **Velayudhan** (2013) was recruited from industry to provide strength in whole bioprocess modelling while **Balabani** (2011) provides additional strengths in experimental fluid mechanics and microscale flows.

• **Early career appointments**: **Mukhopadhyay** (2008) and **Simaria** (2013) were recruited to extend CfIM activities in the important area of global vaccine manufacture and to strengthen Decisional Tools research. **Nesbeth** (2009) was brought in to build capacity in aspects of synthetic biology. **Tang** (2009), **Shearing** (2011) and **Stamatakis** (2012) strengthen our work on Energy by their expertise in solar energy catalysis, fuel cells and catalysis modelling. **Kuhn** (2012) extends our research in advanced manufacturing through his work in intensified chemical processes. **Lee** and **Yazaydin** (2013) strengthen our research in porous, colloid, polymeric materials. Finally **Ducci** (2011) enhances our capabilities in experimental methods for fluid and mixing dynamics.

• **Sustainability:** Within the UoA our strategy is to enhance and develop strength in UCL Grand Challenge areas and our overarching Research Themes. Sustainability is ensured by: (1) Recruiting and supporting researchers with strong track records of fundamental research and a desire for impact (see REF3a) and giving them freedom to pursue their creative ideas. (2) Organising staff into Research Groups that bring together people with overlapping interests into a critical mass. (3) Encouraging groups to align with UCL's Grand Challenges to pursue strategic cross-disciplinary work with other parts of UCL and beyond. (4) Supporting staff to identify Research Council and industrial funding opportunities with input from senior academic staff and **three Faculty Research Facilitators** providing internal assessment of ideas and proposals.

• **Recruitment and equal opportunities:** The **UCL Recruitment and Selection Policy** sets out to ensure, as far as possible, that the best people are recruited on merit and that the recruitment process is free from bias and discrimination. UCL's procedures take into account equal opportunities policy and legislation including the Equality Act 2010 and the Data Protection Act 1998 and UK Immigration legislation. Within the UoA both BE (lead: **Micheletti**) and CE (lead: **Sorensen**) gained **Athena SWANN Silver Awards** in 2013. Each UoA department has a designated Departmental Equal Opportunities Liaison Officer, whose role is to monitor the implementation of equal opportunities policies and to provide advice to students and staff.

• **Career progression and promotion:** UCL lays down a framework for the achievement of excellence in 'Excellence and the UCL community: a shared endeavour' and has well established processes to support academic staff and researchers toward this. Total workload for staff including non-research aspects is assessed annually and progress is appraised by HoDs through the **UCL Staff Review and Development Scheme**. The UCL-wide Professional Development Programme is open to all staff who must identify a minimum of three activities per annum as part of their appraisal. UCL's HR Organisation and Staff Development team provides learning and development services for staff. New academics participate in this programme and take mandatory courses in the **UCL Centre for the Advancement of Learning and Teaching** in grant writing, research student supervision and research management. All staff are aligned with at least one established Research Group and junior staff are assigned a mentor. Promotion procedures are clearly specified, with emphasis being placed on research performance; both scholarship and knowledge transfer.

• **Fellowships, sabbaticals and secondments:** All staff are encouraged to apply for these to further develop their research expertise. Competitively won fellowship successes include: Royal

Academy of Engineering (RAEng) Leverhulme Trust Senior Research Fellowship (**Eames** 2010-11, **Angeli** 2011-12), RAEng Fellowship (**Shearing** 2012-16), EPSRC Advanced Research Fellowship (**Ducci** 2007-12), EPSRC Manufacturing Fellowship (**Velayudhan** 2013-2018). Staff benefit from sabbatical leave for a period of one term after three years qualifying service with UCL (e.g. **Zangeneh** 2013-14). Research active academics returning from maternity, adoption, extended carer's, or long term sickness leave are entitled to one term of sabbatical leave to enable them to more quickly re-establish their research activity. Secondments are used to help build strategic overseas and industrial relationships particularly to **UCL Australia**: Director & BHP Billiton Chair (**Simons** 2012- to date) and Santos Chair of Energy & Resources (**Fraga** 2011-12).

2. Research Students and Doctoral Training Centres (DTC): The UoA has been a major recipient of EPSRC DTC funds and provides a high quality environment for doctoral training. UoA staff co-ordinate two Centres. The £6.5M industrial DTC in Bioprocess Engineering Leadership (**Lye**) is a well-established "model centre" (EPSRC review 2011). To date it has completed 130 EngD projects with 66 different companies and 97% of doctoral graduates have progressed to relevant industry careers. Refunded in November 2013, with an increased focus on Synthetic Biology manufacturing, it is well aligned to our future research objectives. The £2.4M DTC in Emergent Macromolecular Therapies (**Dalby**) was established in 2012 and has a specific remit to establish a national network of bioprocess researchers associated with the CfIM (REF5b). Both centres support collaborative projects within the UoA and across UCL, often in conjunction with other DTCs including CoMPlex, the DTC in Energy Demand and the DTC in Urban Sustainability. UCL Impact Studentships support industry collaboration (see REF3a). In total 154.5 students have graduated over the REF period (2.85 per FTE). Current Research Student (RS) enrolments stand at 60.3 (ME), 73 (CE) and 122 (BE) giving an **average of 4.7 students per FTE**.

Institutional training and support: The **UCL Graduate School** oversees and supports graduate training across UCL. Students are recruited from a wide range of disciplines, including the physical and life sciences and engineering, predominantly from the top universities in the UK, EU, America, and China. RSs are funded from different national and international sources, including UK Research Councils, UK Charities, the European Commission, UCL internal schemes (UCL Doctoral Training Account, Impact Studentships etc.) and industry. The majority of international students are supported through overseas government studentships. Funding is typically for 3.5 years (PhD) or 4 years (EngD). All RSs attend **Graduate School Skills Development Programme** courses which align with **Vitae Researcher Development Framework** requirements.

Departmental support: PhD students initially register for the Master of Philosophy (MPhil) degree and upgrade to PhD registration by 12-18 months if progress is satisfactory. This requires successful completion of a transfer thesis and independent internal viva. EngD students initially register for an MRes and upgrade to EngD registration upon MRes completion; they undertake a defined set of taught courses (225 Credits) throughout the EngD. All RSs are allocated primary and secondary supervisors, with complementary skills, and industrial supervisors as appropriate. RSs are inducted into departments by the **Graduate Tutor** and are introduced to UCL Health & Safety requirements, the Code of Practice for Graduate Research Students, Academic Regulations and Guidelines for Research Students. The Graduate Tutor looks after the welfare of the students and assists with progress monitoring. The **UCL Graduate School E-log** provides a record of RS progress and supervisory meetings. RSs present to their peers and academic staff in Research Group and departmental seminars and progress is monitored by departmental Exam Boards.

d. Income, infrastructure and facilities

1. Research Income: Research expenditure over the REF period totals £25.6M corresponding to £95k p.a. per FTE; or £125k p.a. excluding staff recruited in the last 3 years. The success of investment in new staff (REF5c) is reflected by a **37% increase in expenditure between 2008-2013** while **current research income totals £61.4M which is already over 2-fold higher than total REF2014 expenditure**. A common strategy across the UoA supports staff to identify, submit and win competitive research grants, either individually or within a larger team. All staff are associated with at least one **Research Group** (REF5b). Each group has an internationally recognised Chair responsible for defining research and grant bidding strategy, supporting new staff and promoting research activity and impact (REF3a). **Departmental Research Committees**, which include HoDs, departmental Research Co-ordinators and Research Group Chairs, monitor

progress (grant income, outputs etc) and co-ordinate larger, multi-disciplinary proposals. Various **Industrial Advisory Groups (IAGs)** help develop research strategy and advise on impact delivery (REF3a). Our **Faculty Research Facilitators** (REF5c) provide guidance on Faculty and institutional initiatives and also help co-ordinate larger proposals. Examples of the success of these strategies (see REF5b for details) include: winning EPRSC and industrial funding, from 25 companies, for the CfIM in Emergent Macromolecular Therapies in 2011 (a Macromolecular Bioprocessing Group initiative); securing one of five EPSRC "Frontier Engineering" centres in Nature Inspired Engineering (a Faculty initiative) in 2013; establishment of UCL Energy Technologies (an institutional initiative led by the Centre for CO_2 Technology) in 2013.

A strong and supportive enterprise culture also supports income generation in line with the **UCL Enterprise Strategy** (see REF3a). All UoA staff have considerable engagement with industry and have formed a number of successful spin-out companies (see REF3b Impact Case Studies). DTC awards, CASE awards and UCL Impact Studentships are used to facilitate industry collaboration with a wide range of companies (see REF3a for details). Consultancy activity aligns with our research priorities and provides further support for our research. Exemplar cases are code development for BP to support their business case (**Eames**) and consultation on the science related to legislation for scrubber discharges from ships for the International Maritime Organisation (**Greig**). A 2013 **£3M HEFCE Catalyst Fund award** on "Critical Interventions in the UK Life Sciences Value Chain" (**Lye**) supports two Enterprise Fellows, linking us with the Life Science Catapult Centres, and the establishment of UCL laboratories at the Stevenage Bioscience Catalyst to support early stage spin-out companies (in partnership with the University of Cambridge).

2. Research Infrastructure:

2.1 Space: The main infrastructure investment over the REF period has been the new **£11.3M Engineering Front Building**. This provides meeting and seminar rooms, a Faculty Office for the Research Facilitator team and offices for UoA12 staff. The main laboratory expansion has been the acquisition of 1200 m^2 of new space adjacent to the existing BE pilot plant (see below). A £2.5M investment by UCL in 2013 enabled conversion into high quality, contained laboratories supporting specialist studies on the manufacture of viral vaccines and human cells for therapy. Relocation of existing BE activities into this new space facilitates expansion of the Centre for Nature Inspired Engineering activity (REF5b). Materials discovery and processing is a key growth area for UCL, and the UoA benefits from this expansion. In particular a new **Materials Discovery Hub**, led by CE and UCL Chemistry, is being established as a multidisciplinary Centre of Excellence in materials research. Over £1.5M is being invested in refurbishment as well as state-of-the-art materials processing and characterisation equipment. These facilities will complement the existing cutting-edge equipment and multi-million pound investment in the **London Centre for Nanotechnology**. A further £1.5M of support to establish **The Institute of Making** (www.instituteofmaking.org.uk) provides dedicated space and workshop facilities in support of multidisciplinary materials research and also acts as a focus for the Unit's public engagement activities (see REF3a).

2.2 Technical Support and Fabrication Facilities: Research within the UoA is supported by a range of high quality Technical Staff (8 FTE in total) responsible for laboratory operation and training of researchers on specialist equipment items. In addition, the Unit operates a range of specialist workshop facilities that underpin Research Group activities. UCL has invested over £1.5M during the REF assessment period in expansion of these facilities reflecting the importance of experimental work in our UoA. Each of the facilities listed below is based in and managed by a specific department but are heavily used by staff across the UoA.

• **Macroscale manufacture and machining (ME).** This facility of 500 m^2, is supported by 8 highly skilled technical staff and is equipped with a range CNC machines, including 3 and 4 axis machines, and lathes. The focus is on fabrication of research equipment with length scales from 5mm to >2m. Exemplar applications include the fabrication of engine test rigs and wave tanks.

• **High Precision Design and Fabrication Facility (BE).** This facility is 300 m^2 and is supported by 5 highly skilled technical staff. Between 2012-2013 it was completely refurbished and equipped with new precision CNC milling machines supporting fabrication of equipment with length scales from 0.1mm to >10cm. Exemplar applications include microreactor and photobioreactor fabrication.

• **Micro/Nanoscale manufacture.** This utilises a cross institutional facility based in the London Centre for Nanotechnology (www.london-nano.com/) housed in 1300 m^2 of bespoke clean rooms

manned by dedicated staff. It facilitates fabrication of specialist devices with scales ranging from 10nm - 10mm and supports microfluidic research in both BE (**Dalby, Szita**) and CE (**Gavriilidis**).

• **Computing and Electronic Services Workshop (CE).** This facility is 75m^2 and employs 5 technical staff. They work closely with the mechanical workshops on fabrication of electro-mechanical devices and research rigs and support computing infrastructure across the UoA.

2.3 Institutional Support for Research Access and Outputs: UoA staff benefit from extensive access to electronic journals and databases. UCL Library Services has invested over £2.7M in upgrading facilities across UCL since 2008 of which £1.1M specifically benefits UoA12 staff using the **UCL Science Library**. This includes flexible, IT-enabled spaces for individual and collaborative work and a further £1M investment in new e-resources. In line with the UCL Library Services Strategy (2011-2014) **UCL Discovery** (discovery.ucl.ac.uk/) has been launched to facilitate access to all UCL research outputs with additional support for open access publications.

3. Specialist Research Facilities: The Unit benefits from considerable investment in specialist research facilities and equipment supporting research across the Unit and UCL as a whole. It also collaborates in cross-institutional initiatives such as creation of the **London Centre for Nanotechnology** (see above), a joint venture between UCL and Imperial College. Funds for these facilities are either raised externally or represent institutional priorities for investment. In addition, the Unit benefits from donated equipment items from industry e.g. provision in 2012 of >£0.5M of single-use bioprocess equipment. Specialist facilities in each department are summarised below.

• **Biochemical Engineering** research is facilitated by access to a £25M bioprocessing pilot plant, The Advanced Centre for Biochemical Engineering (ACBE), equipped with a range of bioreactors (up to 500L), associated downstream processing (DSP) equipment and analytical facilities. In 2010 a further £1M capital investment established a new **Responsive Bioprocessing Facility**. This is unique in the academic sector focussing on single-use, 'whole bioprocess' studies. Company equipment donations have enabled us to equip the RBF with a range of single-use bioreactor and DSP technologies. Further specialist facilities include the £5M **Centre for Micro Biochemical Engineering**, which is equipped with a suite of 6 robotic platforms for high throughput bioprocess studies (Tecan & QPix) and facilities for rapid microfluidic device fabrication and evaluation.

• **Chemical Engineering** research has benefitted from a range of investment to support new and existing staff. These include refurbishment of laboratories for photocatalysis, electrocatalysis and chemical reaction engineering studies supported by a Wolfson grant (£200k) with matched UCL funding and Faculty/CIF funding to enable a full upgrade of our unique high power pulsed X-ray imaging facility (£360k) for fluidisation and gasification studies. These complement existing state-of-the-art pilot scale flow facilities, developed to study liquid-liquid flows relevant both to the petroleum and process industries. The flow rigs are equipped with specialised instrumentation for studying flow properties (£120k) and we have invested in new micro-PIV equipment with UV illumination and multicolour imaging (>£200k) to enable study of microscale flows.

• **Mechanical Engineering** research makes extensive use of a 25m long deep water wave tank and a shallow flume/wave tank equipped with computer controlled wave generator and towing tank for testing ship designs and energy extraction devices. The **Jaguar Centre** (REF5b) contains 7 integrated engine test cells (3 optical engines, 4 thermodynamic engines) equipped with dynamometers, high temperature/pressure combustion facilities and gas analysers. High resolution laser imaging facilities consisting of 10 argon-ion, Nd:YAG, diode and tunable dye lasers enabling PIV, LIF and LDA flow and flame measurements. Further facilities include a new ISO8 clean room facility for microfluidic work, material testing devices (2 x 100kN Instron) and 3 laser vibrometers.

Staff also make extensive use of UCL's **centralised research computing facilities**. These include the Legion HPC service, a free to access general purpose computing cluster, the Unity SMP service, which is a shared memory service (672 GB), and the Condor HTC service which comprises a heterogeneous cluster and 1 GPU clusters (16 GPUs 448 CUDA cores each). These support work, for example, on tsunami modelling, option pricing and ophthalmology (**Eames**).

e. Collaboration or contribution to the discipline or research base

Academic collaborations from cross-departmental to international level are encouraged and supported across the UoA. Exemplar cases provided below illustrate interactions from common

funding to shared resources. All entries in this section occurred within the REF assessment period.

1. Funded Collaborative Research: (a) International: International grants and training network activities are funded from a variety of sources, e.g. EU FP7: CO2QUEST (Coordinator: **Mahgerefteh**); MICROTOOLS (Coordinator, **Szita**); BIONEXGEN (**Lye**); Synmod (**Szita**); Emergence SynBio Network (**Szita**); BIOtrachea (**Mason**); CO2PipeHaz and FIREPROOF (**Andrews**); FAROS (**Andrews**, **Greig**); MARINELIVE (**Greig**), ERA-NET Industrial Biotechnology: IPCRESS (Coordinator, **Nesbeth**); HyPerIn (**Micheletti**); Office of Naval Research (ONR): NICOP programme on Ship Layout (**Andrews**); ACCeSS programme (**Bucknall**), Australian Department of Defence and UK MoD Dstl SS Group (**Andrews**); The Lloyds Register Educational Training Centre (**Wu**) involving UCL, Shanghai Jiaotong and Harbin Engineering University. EPSRC UK/India 'Mind the Gap' Fuel Cells (**Brett**).
(b) National or Regional: An exemplar case of regional collaboration is the London Regenerative Medicine Network (led by **Mason**) which brings together 200-250 stakeholders each month. Exemplar cases of multi-institutional collaborative research consortia are: EPSRC Programme Grant on Multiphase Flows (**Angeli**); EPSRC Sustainable Chemical Feedstocks (**Lye**); Shipping in Changing Climates (**Bucknall, Greig**); Low Carbon Shipping: a systems approach (**Bucknall, Greig**); Research Network with Jaguar Cars (**Aleiferis**); UK Consortium on Mesoscale Engineering Sciences (**Lao**); UK Consortium on Computational Combustion for Engineering Applications (**Lao**).
(c) Institutional: A number of research centres across UCL support collaboration and researcher exchange and play a facilitating role in the Unit's research. These include: UCL Centre for Maths and Physics in the Life sciences and Experimental Biology (CoMPLEX), UCL Materials Chemistry Centre (MCC), London Centre for Nanotechnology; UCL Energy Institute. Other UoA12 activities draw on cross-institutional strengths e.g. Reducing the Cost and Prolonging the Durability of Hydrogen Fuel Cell Systems by *in-situ* Hydrogen Purification and Technology Hybridization (EP/K021192). Biomedical and clinically focused research is supported by collaboration with UCL Hospitals and **UCL Partners** which allows access to a patient population approaching 6 million.

1.1 Funded Networks and Industrial Consortia: IMRC in Bioprocessing (**Hoare and colleagues**, 2002-2012); CfIM in Emergent Macromolecular Therapies (**Titchener-Hooker**, **Farid**, **Dalby**); Biocatalysis integrated with Chemistry and Engineering (BiCE) Programme (**Lye and colleagues**); GSK Centre of Excellence in Bioprocessing (**Hoare**, **Lye**, **Dalby**); BBSRC SynBion network (**Ward**); STFC Global Challenge Network in Battery Science and Technology (**Shearing, Brett**, ST/K00171X/1); EPSRC Grand Challenge Network on CO_2 utilisation (**Angeli**); EPSRC Dial-a-Molecule Network (**Gavriilidis**); Jaguar Centre (**Aleiferis and colleagues**) The Unit is also heavily engaged with industry to develop TSB and ETI industry-collaborative grants (18 in total to date). These have been led by: **Aleiferis, Baganz, Balabani, Balachandran, Bracewell, Farid, Hoare, Ladommatos, Lettieri, Lye, Mason, Mukhopadhyay, Veraitch, Wall and Zhou.**

2. Contribution to the Discipline: Contributions to the discipline are formed by peer review activities to national and international funding agencies, plenary/keynote talks, awards, etc.

2.1 Funding/Advisory Bodies: (a) National: Member of EPSRC SAN (**Titchener-Hooker**) and Peer Review College (**Andrews, Bogle, Brett, Ducci, Eames, Fraga, Gavriilidis, Ladommatos, Lettieri, Lye, Mahgerefteh, Papageorgiou, Sorensen, Titchener-Hooker**); Member of BBSRC main panels (**Dalby, Ward**); Member of MRC Peer Review College (**Wall**); BERR/BIS Innovation and Growth Teams (**Hoare, Lye**); BIA Cell Therapy & Regenerative Medicine Industry Group (**Mason**); BBSRC/EPSRC/TSB Bioprocess Research Industry Club Steering Group, (**Titchener-Hooker**); BBSRC Integrative Systems Biology Strategy and Bioscience Skills and Careers Strategy Committees (**Bogle**); BIS National Measurement System for Chemical and Biological Metrology (**Brett**); Advisory Committee for Decontamination Science and Technology (**Eames**).
(b) International: Agence Nationale de la Recherche, France (**Wall**); Canadian Centre for Regenerative Medicine, Blond McIndoe Research Foundation (**Mason**), Synthetic Biology Task Group, European Federation of Biotechnology (**Nesbeth**); Swiss National Science Foundation and Swiss Federal Institute of Technology (**Fraga**, **Lye**), EU ERA-NET in Industrial Biotechnology (**Lye**); Qatar National Research Fund (**Bogle, Ladommatos, Mahgerefteh**); Italian Ministry of Education, Universities and Research (**Lettieri, Mahgerefteh**); Academy of Finland (**Lettieri**); Dutch Technology Foundation STW, German DFG (**Sorensen**); Norwegian Research Council (**Angeli, Andrews**), NSERC Canada (**Angeli**); ERC (**Gavriilidis**); FP7 expert evaluator (**Greig**).

2.2 Plenary and Keynote Presentations: Representative examples include: ESCAPE19 (2009, **Bogle**); ISCRE22, Maastricht (2012, **Coppens**, **Gavrillidis**); International Symposium on Feeds and Processes for the Production of Clean Fuels, Ixtapa, Mexico (2011, **Coppens**); 12th International Conference on Clean Energy, Xi'an, China (2012, **Tang**); American Chemical Society, (2010, 2013, **Hoare**) (2012, **Titchener-Hooker**); International Society of Electrochemistry, France (2010, **Brett**); IBC Cell Line Development and Engineering (2010, **Farid**); AIChE (2010, **Baganz**) (2011, **Titchener-Hooker**); bioProcessUK (2011, **Hoare**); BIO World Congress on Industrial Biotechnology and Bioenergy (2009, **Dalby**), EuropaBio's Forum for Industrial Biotechnology (2009; **Dalby**), Gordon Research Conference on Biocatalysis (2010, **Dalby**), Recovery of Biological Products (2010, **Micheletti**) (2011, 2012 **Farid**): Recent Advances in Fermentation Technology, Florida (2011, **Micheletti**); Cell Culture Engineering XIII (2012, **Farid**).

2.3 Learned Society Engagements and Committee Membership: RAEng: Membership Committee (**Titchener-Hooker**); IChemE: Membership Committee (**Titchener-Hooker**), Special Interest Groups: Applied Catalysis (**Gavriilidis**); Biochemical Engineering (**Lye**, Chair 2005-2009, **Veraitch**); Safety and Loss Prevention (**Mahgerefteh**); Fluid Separations (**Sorensen)**; EFCE WP on Chemical Reaction Engineering (**Gavriilidis**); AIChE International Committee-Chair (**Coppens**); RINA Council and Executive Committee (**Andrews**, Vice President since 2006, Vice Chairman of Council/Executive Committee 2011-12); Society of Chemical Industry (SCI): Biotechnology Group (**Baganz**); Royal Society of Chemistry (RSC): Biotechnology Group (**Dalby**); EFCE Section on Sustainability (**Lettieri**); IMarEST: Member of Council (**Greig**).

2.4 Prizes and Awards: Queen's Anniversary Prize in Higher Education (2013, **BE**) ACS Alan Michaels Award (2013, **Hoare**); bioprocessUK Dunnill Award (2011, **Hoare**); RAEng ExxonMobil Excellence in Teaching Award & Gold Medal (2009, **Farid**); IChemE: Frank Lees Medal (2009**, Mahgerefteh**); Young Moulton Medal (2012, **Lettieri**); Hutchison Medal (2012, **Papageorgiou**); Donald Medal (2013, **Titchener-Hooker**); Innovation and Excellence Award in Bioprocessing (2010, **BiCE programme,** see REF 3b); AIChE Pharmaceuticals Division Plenary Award (2010, **Baganz**); RSC: Rita & John Cornforth Award (2010, **BiCE programme,** see REF 3b); Catalysis Engineering Science & Technology Award Lecture (2012, **Coppens**); ICE: Baker Medal (2011, **Brett**); De Nora Prize on Applied Electrochemistry (2009, **Brett**); Telford Prize (2013, **Eames**).

2.5 Fellowships: FREng (**Andrews, Bogle, Titchener-Hooker**), FIChemE (**Angeli, Gavriilidis, Lettieri, Lye, Mahgerefteh, Simons, Sorensen**), FIMechE (**Andrews, Ladommatos**), FRINA (**Andrews**), FRCS, FRCSI (**Mason**), FASME, FIP (**Luo**), FIMarEST (**Greig**), FIMA (**Eames**).

2.6 Conference Organisation: Representative examples include: Engineering Conferences International (ECI): Vaccine Technology (2012, 2010, **Mukhopadhyay**); Cell Therapy Bioprocessing (2011, 2012, 2013, **Mason**), ACS: Recovery of Biological Products Conf. Series Board Chair (2010-2012, **Titchener-Hooker**); Recovery of Biological Products (2010, **Titchener-Hooker**), IChemE: Integrated Continuous Biomanufacturing (2013, **Titchener-Hooker**); CCS From Cradle to Grave: The Technical and Safety Challenges (2012, **Mahgerefteh**); Distillation & Absorption (2010, **Sorensen**), IMA Medical Devices and Surgical Procedures (2012, **Eames**); EUROMECH Interfaces in Turbulence (2011, **Eames**); ESCAT Workshop Chair (2013, **Veraitch**); Scale-Up and Manufacturing of Cell-Based Therapies (2012, **Mason**); European Congress of Chemical Engineering (2011, 2013, Sorensen), European Conference on Microfluidics (2010, 2012, **Angeli**); Int Symposium on Multiphase Flow and Transport Phenomena (2012; **Angeli**); Electrochem (2009, **Brett**); International Conference on Microreaction Technology (2010, 2012, **Gavriilidis**); International Symposium on Chemical Reaction Engineering (2008, 2012, **Gavriilidis**); European Symposium on Computer-aided Process Engineering (2011, and hosting it in 2012, **Bogle, Fraga, Papageorgiou**); Congress on Evolutionary Computing (2011, **Fraga**). Intl. Marine Design Conf. (2009, 2012, **Andrews**); Intl. Naval Eng. Conf. (2010, 2012, **Greig**).

2.7 Editorial Positions: Listed only for Q1 ranked journals: Biotechnology and Bioengineering (**Hoare**), Chemical Engineering Research & Design (Editor-in-Chief, **Sorensen**), Chemical Engineering Science, Powder Technology, Chemical Engineering & Technology (**Coppens**); Current Opinion in Chemical Engineering (**Papageorgiou**), Int. J. of Chemical Reactor Engineering (**Lettieri**), IET Renewable Power Generation (**Brett**), Fuel (**Aleiferis**), Int. J. of Engine Research (**Ladommatos**), Biochemical Engineering Journal (**Lye**), Journal of Chemical Technology and Biotechnology (**Baganz**); Regenerative Medicine (Senior Editor, **Mason**).