Institution: University of Liverpool

Unit of assessment: 12 - Engineering

Section 1. Unit context and structure, research and impact strategy

1.1. Research Structure and Context

Our vision for Engineering at Liverpool is to deliver creative and impactful research of the highest international standards. We are guided by the principles that our research:

- addresses major current and future strategic and intellectual global engineering challenges;
- ensures relevance, through meaningful engagement with industry and wider society;
- is pursued ethically and with integrity; respecting life, law, the environment and public good.

We strive to foster these principles, providing an inclusive and fulfilling place to work.

Engineering research spans four departments as shown below. In this assessment period, academic research staff working within Engineering disciplines have increased significantly from 58 to 92.6 FTE. Staff included in the UoA12 submission are shown capitalised (e.g. NAME).

Engineering research in the University of Liverpool – UoA12

School of Engineering (SoE)		Institute of Life Course and Medical Sciences (ILCaMS)	School of EEE & Computer Science (EEECS)
Dean: Prof Eann PATTERSON		Dean: Prof Pete Clegg	Dean: Prof Katie Atkinson
Civil Engineering & Industrial Design (CEID) Prof Ping DONG Research themes: - Industrial Design - Environmental Engineering - Infrastructure - Structures	Mechanical, Materials & Aerospace (MMA) Prof Rob POOLE Research themes: - Aerospace - Biomedical Eng. - Eng. Dynamics - Materials - Manufacturing - Nuclear - Virtual Eng.Centre	Eye and Vision Science Prof Rachel WILLIAMS Research themes: - Materials & Technology - Therapeutics and Interventions - Behaviour and Prevention	Electrical Engineering & Electronics (EEE) Prof Alan MARSHALL Research themes: - Data Sci. & Signal Processing - Energy Technologies - Networks & Comms. - Sensors, Diagnostics & Biomed. Devices -Technol. Plasmas

Together the four departments provide a comprehensive environment, fostering interdisciplinary research, shared equipment and facilities.

1.2. Progress in fulfilling our Research Strategy

Our REF 2014 submissions articulated three core strategic approaches:

S.1. Increased alignment with the University's research themes, embodied in the "University Strategy 2026", where it encompasses engineering research, namely*: Liverpool Digital; Personalised Health; Advanced Materials; Infectious Diseases;* more recently *Climate Futures;* and their application to challenges in energy, health & wellbeing, security and resilience.

S.2. Strategic increase of interdisciplinary research in the areas of: biomedical science and engineering; data science & signal processing; environment and uncertainty; energy and nuclear technologies; materials and manufacturing.

S.3. Increased orientation of research infrastructure towards addressing regional, national and international challenges.

Our progress in delivering these objectives is outlined below:

S.1.1. Liverpool Digital is one of seven University-wide key research themes formally adopted in 2018. Significant progress includes the development of a £12M (including £5M from the Liverpool City Region Strategic Investment Fund) new-build Digital Innovation Facility (DIF) which will become operational in 2021. The DIF expands research across the Unit in autonomous systems, robotics; virtual engineering and design; and supports external collaboration and impact. Within MMA, a coordinated £150k investment has established the @LERT robotics laboratory. MASKELL is co-sponsor for UoL's Digital Everywhere program, which involves £3M internal investment to kick-start adoption of digital technology across the institution's research, education and professional services.

S1.2. Sensor City (pictured right), headed by SPENCER, is a joint initiative between the University and Liverpool John Moores University and is a flagship University Enterprise Zone. This global innovation hub applies fundamental research to SMEs, enabling industry and academic partners to translate novel and innovative sensor concepts into commercially viable solutions through rapid prototype development and laboratory testing facilities. Sensor City houses spin-out companies, including Hexsor Scientific and Q-Technologies Ltd [TAYLOR].

Sensor City leads the Liverpool 5G-testbed, a consortium of public sector health suppliers, NHS, university researchers, local SMEs and a leading UK 5G technology vendor, with £3.5M funding from DCMS. Liverpool 5G has created the largest 5G mm-wave mesh network in the UK (second largest in the world) and has demonstrated a fully-connected care home.

S.1.3 The Materials Innovation Factory (MIF), which opened in 2017, facilitates cross-cutting materials research. The £81M facility integrates advanced materials research with analytical, computational and robotic equipment to accelerate materials development. MMA research arising from this strategic investment features: 3D printing of rheologically-complex materials; development of functional thin film materials and manufacturing processes; advanced robotic handling systems; and energy materials.

S.2.1. The newly established Nuclear Research Group was created by strategic appointments in nuclear materials (WHITTLE and PATEL); an NNL / RAEng appointment in nuclear engineering computational modelling (MERK) and collaborations from across the Faculty of Science and Engineering. A strategic partnership agreement with the National Nuclear Laboratory (NNL) provides access to NNL's Central Laboratory at Sellafield. Another partnership with the University of Manchester provides access to the Dalton Cumbria Facility, including an accelerator and a cobalt radioactive source. PATTERSON is the academic lead of a £2.9M initiative, funded by BEIS with Amec Foster Wheeler, for a UK Digital Reactor Design partnership to improve the design and build of new nuclear reactors, with optimised operating lifetime performance. A partnership with National Tsing Hua University in Taiwan, established a dual PhD program, which enabled access to the THOR research reactor on the NTHU campus.

S.2.2. The cross-faculty Biomedical Science and Engineering Research Group (MMA and Eye and Vision Science), develops clinically relevant medical devices and therapies. Research spanning biomaterials and tissue-engineered products has led to impact cases in the development of novel tamponades (WILLIAMS) and tonometry (ELSHEIKH) to improve management of an array of clinical eye conditions. Translational research is facilitated by our close links with St Paul's Eye Unit and the Clinical Eye Research Centre at the Royal Liverpool University Hospital. ELSHEIKH's Knowledge Transfer Partnership (KTP) with UltraVision to

develop a finite element model of the keratoconic cornea was graded 'outstanding' by Innovate UK and led to new product developments worth £2M to Ultravision in licensing income.

S.2.3. Research into advanced Battery Materials and characterisation, has been the focus of increased collaboration between Engineering and Chemistry within the national Faraday Institute. The recruitment of BROWNING and MEDHI, has led to new world-class, in-situ electron microscopy techniques to inform the development of advanced battery technologies with Hardwick and Rosseinsky, FRS. This includes a £1M multi-institutional Faraday project led by BROWNING on 'Quantitative Imaging of Multi-Scale Dynamic Phenomena at Electrochemical Interfaces', resulting in UoL partnering in three of four UK research hubs of the ISCF Faraday Battery Challenge.

S.3.1. *Manufacturing the Future* research in additive manufacturing has driven collaboration with internationally-leading biomedical companies, such as Stryker, and AM equipment manufacturers including Renishaw. This research underpins an impact case covering 3D metal printing technology and production processes for the manufacture of implantable osseo-integrating bio-structures. The research techniques Sutcliffe and colleagues developed now forms the global backbone of industrial 3D printing for metals. Investment (£300k) in a newly refurbished laboratory for Additive Manufacturing has provided a focal point for facilities funded through EPSRC and from Renishaw plc.

S.3.2. Research in *Data Science & Signal Processing (EEE)* has focused on developing ground-breaking, translatable algorithmic solutions across multiple sectors in both industry and government. This has led to a £7M EPSRC-funded Centre for Doctoral Training in Distributed Algorithms and the establishment of an interdisciplinary Liverpool Big Data Network (LBDN), comprising >100 academics united by a common interest in developing and applying Big Data – identified as one the UK Government's 'Eight Great Technologies'.

S.3.3. Addressing regional challenges, LCR 4.0, a £10M knowledge transfer project (funded by ERDF) has supported > 300 SMEs in Liverpool City Region with access to expertise, technology and collaboration opportunities to boost productivity and drive innovation to adopt Industry 4.0 technologies. The project was delivered through a consortium led by Sensor City and VEC (2016-2019). Resulting economic gains included >80 new jobs and £22.5M GVA, LCR 4.0 is recognised as an exemplar initiative nationally, listed as one of the Top 100 European digital champions in the Financial Times (2018) and is referenced as a best practice initiative in the Made Smarter Review (2017).

S.3.4. The *Networks and Communications* group has led a strategic drive to increase national and international collaborations. MARSHALL is UK Chair of the flagship Jiangsu–UK 20+20 World-Class University Consortium (jointly spearheaded by the British Council, Universities UK, and the Jiangsu Provincial Department of Education) with over 30 leading universities from the UK and Jiangsu province, collaborating to strengthen international academic research partnerships and includes a multi-party Doctoral Training Centre in Dependable Autonomous Systems.

S.3.5. Our expertise in the design and development of reliable, and verifiable, autonomous systems is being used to develop future generations of autonomous robotic systems for use specifically in nuclear, offshore, and outer-space. JUMP and PATCHETT are part of an interdisciplinary team involved in research to develop new robotic technologies to improve efficiency and reduce human exposure to extreme and hazardous environments - part of £2M funding awarded through participation in three research hubs funded under the Government's Industrial Strategy Challenge Fund.

S.3.6. Liverpool's Advanced Networks Research Group (ANRG) specialises in risk assessment and security threat modelling – an ever increasing national and international challenge. Research led by MARSHALL has led to the development of a next-generation network security technology, SpriteGuard™, which allows automatic attack detection and prevention. The research underpinning SpriteGuard™ has been funded through the EU, EPSRC and subsequently by the North West Fund for Venture Capital). SpriteGuard™ is the only security system that can sit

alongside the existing Wi-Fi environment, guarding all devices connected to open and public Wi-Fi networks. The product is currently deployed in multiple hotel chains in London and New York.

1.3. The Research Strategy for the next 5 years

Our core research strategy in the period has focused on building critical mass through alignment with the University's themes; enhancing interdisciplinary links; and increased internationalisation. Developing these core principles, the Research Committees of the constituent departments have identified key steps for the next five years:

F.1. ***"Sustain and Grow"*** our research spaces, laboratories, facilities and equipment;

F.2. ***"Civic and Global"*** – to work for the benefit of our local community, whilst extending a global reach, ensuring impactful outcomes regionally, nationally and internationally.

F.3. ***"Invest and Develop"*** – recruiting talented researchers at every career stage and working with them to develop their research;

Within this strategic framework, we intend to continually promote interdisciplinary research and provide an overarching environment of integrity and ethical research. Research plans in these objectives include:

F.1. ***"Sustain and Grow"***:

F.1.1. As part of the University's £1B Estate Strategy, a new building (£42M) for EEE, new research laboratories and clean room will provide an enhanced environment for EEE research. The new facilities will enable capacity building, working in partnership with Sensor City and the Digital Innovation Facility. The establishment of a Centre for thin-film devices focusing on the energy and healthcare themes is planned.

F.1.2. The Digital Innovation Facility (DIF) will provide a new multi-sensory immersive reality venue for researchers in EEE and MMA, complementing existing capabilities in the Virtual Engineering Centre. This will be coupled with targeted expansion in staff and research capabilities in Robotics and Autonomous Systems under a new Institute for Digital Engineering and Autonomous Systems (IDEAS).

F.1.3. Building on the investment made in the Materials Innovation Factory (MIF) in the current REF period, we will continue to strategically align materials engineering and manufacturing. Initiatives include the use of artificial intelligence for the discovery and development of new engineering materials for the built environment and energy applications.

F.2. "Civic and Global"

F.2.1. Building on our REF2014 objective S3, we will target regional partnerships within the Liverpool City Region, working for the benefit of our local business community, including a regional digital innovation business support program (e.g. LCR START led by VEC).

F.2.2. Engineering will contribute to the heart of the Liverpool City Region Combined Authority strategy "Building Back Better" for economic recovery of Merseyside in the post-COVID-19 period. Major themes include the Mersey Tidal Power; investment in a hydrogen fuel network; a National Packaging Innovation Centre; and the low CO_2 Glass Futures research centre for glass manufacture.

F.2.3. The expansion of the DIF will underpin the development of the international Doctoral Training Centre in 'Dependable Autonomous Systems' (S3.4) in partnership with York, Queens Belfast and three universities in China (under the UK-Jiangsu 20+20 initiative). Strategic participation in the UK-China "UCEER" initiative is planned.

F.2.4. Creation of a multidisciplinary Design Institute spanning engineering science, design, innovation, creativity and lifecycle processes. The Institute will integrate research in the Schools of Engineering and Architecture and our partner XJTLU.

F.3. "Invest and Develop"

F.3.1. We have recruited a raft of new and early career researchers to take our research forward. We will use our People Strategy (see Section 2) to help these new colleagues further develop their careers throughout the next REF cycle.

F.3.2. 'Climate Futures' is new a cross-disciplinary research theme for the University. The 'energy solutions' strand of this is led by WHITTLE. Engineering Design is striving to be leaders in advancing design and innovation in developing and emerging areas through a symbiosis of Digital Innovation, Human-Centred Design, and Systems (policy and strategy) Innovation. Future research for the Intervention, Mitigation and Resilience of Climate Change will target geohazards such as landslides, flooding and earthquakes. This builds on ECR appointments in geomechanics (KRABBENHOFT and ZHANG).

F.3.3. We plan further growth of research in Nuclear Science & Engineering, as part of the University's strategic partnership with the National Nuclear Laboratory, and builds on the professorial appointments made in the current REF period.

1.4. The strategy for our Impact Culture

Our continuously evolving Impact Culture is increasingly supported with our research partnerships and innovation office and through strategic investments. The management of impact has been increasingly embedded and monitored within the departments. In the period, our strategy for an impactful research environment is based on the key elements of:

I.1. ***Incubation*** – developing researcher awareness; identifying and resourcing potential impact.

I.2. ***Realisation*** – establishing intellectual property; building partnerships to exploit research and knowledge transfer.

I.3. ***Recognition*** – embedding research in career development; providing space and time; recognition and reward for contributions to impact.

"Incubation" (I.1.) lies at the heart of embedding impact in our research culture. We have adopted a number of mechanisms to facilitate the impact agenda. Examples include: dedicated impact "away days" involving external speakers and impact case study leaders from REF 2014, staff meetings, seminars and newsletters to highlight external knowledge exchange opportunities (i.e. UKRI funding calls and networking events). The introduction of "Impact Lead" roles (and deputies) in each department, together with internal funding mechanisms ("knowledge exchange" vouchers, impact acceleration (IAA) funding) and prioritising resources (time, money, space, sabbaticals) for staff developing significant impact activity, have led to a culture of impact being embedded across the unit. One example, "*Enhanced virtual engineering reduces development times in Nuclear and Aerospace Industries*" (see impact case) has benefitted from strategic use of workload allocation and HEIF funds (£18k EPRSC IAA award).

"Realisation" (I.2.) Strategic mechanisms for researchers to develop impact from their research include: maximising our inter-disciplinary structure to drive the impact agenda, working in partnership across joint research initiatives, industry partnerships, IP-generation activities and industrial secondments.

Inter-disciplinary research on energy is a strong example where we have utilised joint facilities and capabilities between departments and created a unique combination of expertise across the boundaries of engineering, materials, chemistry and physics to make us one of the leading UK institutions for interdisciplinary research into battery energy storage in collaboration with the Faraday Institute (BROWNING, MEHDI and CHALKER).

Fundamental research has been successfully commercialised to realise impact. One example is our work with global med-tech company *Stryker Orthopaedics* (see impact case). This research has contributed to the launch of five families of implants for Stryker's Joint Replacement and Spine franchises, which has been used in more than a million patients, helping to improve lives and wellbeing.

VEC's position as a specialist in providing innovative virtual engineering solutions for real-world industry problems has led to multiple industry partnerships delivering real world impact. A

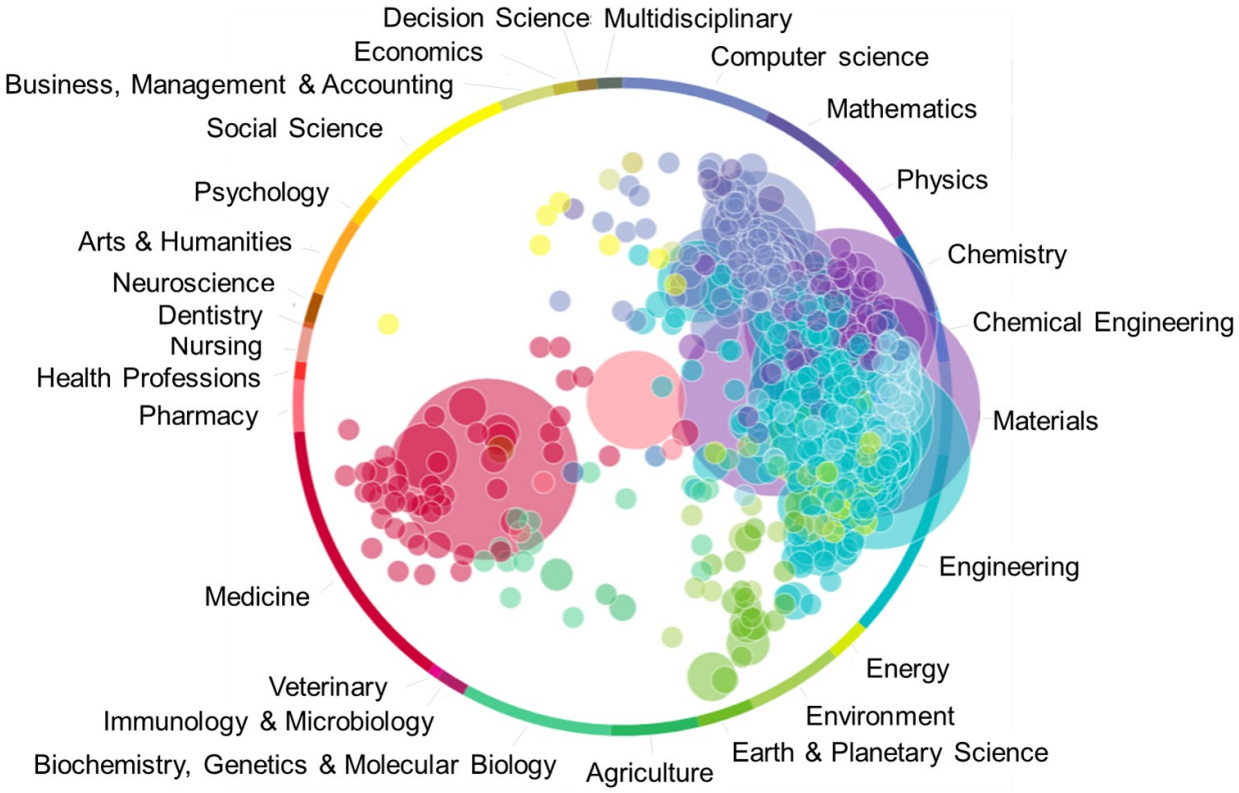
partnership with Sellafield Ltd (2018) to co-develop a mixed reality simulator to train and certify operatives in a controlled environment has generated an estimated £20M cost savings to the organisation. Bentley used VEC facilities and expertise when designing their new SUV and benefited from a reduction in product development time of six months and created 457 new jobs across the supply-chain.

Strategic secondments have also been exploited to achieve impact. From 2015 to 2018 Sutcliffe was seconded as Research Director at Renishaw Additive Manufacturing Products Division (80% FTE) whilst retaining his University position. The collaboration has influenced the development of a range of metal additive manufacturing with Renishaw plc, which now produces high-throughput metal AM systems, exporting more than 300 world-wide, between 2014 and 2019.

"Recognition" (I.3.) The third strand of our impact strategy places the pursuit of impactful research centrally within academic life. The goal is for "impact generation" to be viewed as important as research outputs, award generation and teaching excellence within an academic's role. One way this is facilitated is through promotion and recognition. A notable example is the personal Chair award to ZHAO for his leadership of a 4* impact case in REF 2014, relating to new porous metallic materials. Other promotions include Sutcliffe and WHITE for their impactful research in AM manufacturing and Flight Simulation.

1.5. Interdisciplinary research across the University

In line with strategic aim S2 above, interdisciplinary research has been a focus of our objectives over the 2014-2021 REF period. This focus has helped us establish a critical mass of expertise to address real world challenges. The success of these initiatives is reflected in the broad scope of engineering research in UoA12 which is demonstrated below in terms of the proportions (circle size) and prominence (> towards rim) of outputs during the period identified by Scopus - SciVal research identifiers.



Approximately a third of the output volume of UoA12 is interdisciplinary.

Networks, research groups and centres enable collaborative working, within and across multiple disciplines in areas such as energy and healthcare technologies and materials science. Acceleration of impact is maintained by engaging key stakeholders and end-users to ensure broadest reach and significance is achieved:

- Supported by the Stephenson Institute for Renewable Energy (SIRE), N-STAR (Nuclear Science, Technology and Applied Research) and Sensor City we are developing new options for the generation, delivery and storage of energy. We address environmental and societal impacts of future energy technologies through working cross-institutionally with the National Oceanography Centre, the Risk Institute and the Heseltine Institute for Public Policy.
- The Healthcare Technologies partnership brings together physical and biomedical sciences in a unique interdisciplinary cross-faculty network. The combined expertise aligns cutting-edge facilities and clinical know-how with a clear strategy directed to bring significant improvements to patient outcomes. The cross-faculty work of ELSHEIKH, SHEN and WILLIAMS developing new imaging technologies for the early diagnosis and management of eye diseases (see impact cases) are clear examples.
- International interdisciplinary focus includes significant contributions to several NIHR- and EPSRC-funded projects led by ZHENG and HARDING including £1.1M EPSRC GCRF project "Development of New Low-Cost Point of Care Imaging Technologies for Diabetic Eye Disease in China" which is expected to bring huge benefits to over 100 million people with diabetes.CEID works closely with the Liverpool Institute of Risk and Uncertainty, the School of Environmental Sciences and the School of Architecture. The Creative Design Engineering Lab (Cdel) (led by SAREH) is an interdisciplinary research lab designing and developing innovative engineering structures, robotic systems, vehicles, and products.
- EPSRC funded "Water Antenna" HUANG and Xiao (Chemistry) combines expertise from radio frequency and microwave engineering, chemical and material science to identify the most suitable liquid materials which can be used as antenna. This original and transformative approach focuses on next generation mobile devices and the opportunities afforded by the Internet of Things, working with industrial partners BAE Systems and Huawei.
- The development of cross-disciplinary research has led to the engagement within several CDT's including: Additive Manufacturing (Sutcliffe, BLACK, CHALKER, POTTER); Distributed Algorithms (MASKELL); Photovoltaics (CHALKER, POTTER); Risk (MOTTERSHEAD, PAOLETTI, BEER, FERSON), Nuclear (PATTERSON, PATEL & WHITTLE), Fusion (BRADLEY) and Technologies for Ageing (WALSH, WILLIAMS).

1.6 Research Integrity and Openness

Open research environment and data management: We operate well-established procedures for open access research and data management and adhere to the University Research Data Management policy. The University has an Institutional Repository system which requires all staff to deposit their full text academic output and impact activity for open access compliance. In addition, the UoA makes extensive use of the institutional level secure online environment (Elements) to deposit, share and promote data and information.

An example where UoA12 has moved beyond our baseline commitment to Open Data is COSSAN - A cutting edge open source software designed to quantify, mitigate and manage uncertainty for risk, reliability and resilient analyses, supported by extensive documentation and tutorials and a bi-annual "hackfest" dedicated to the development of the software. The OpenCOSSAN Engine is developed by a large number of researchers from all over the world. The latest version is available as compiled Java or Python library. This allows royalty-free integration of the software with other programming languages. Example case studies where this software has been used includes an analysis of the Grenfell Tower fire by modelling the main components, hazards and factors that contributed to disaster.

Within our environment there is a commitment to: maintaining the highest standards of rigour and integrity in all aspects of research. The mechanisms for this include pre-submission review of proposals by standing peer-panels of the discipline-specific Research Committee. For more strategic Research Council / charitable trust theme calls (e.g. CDTs, hubs, strategic equipment etc.) Faculty- or University-wide panels are assembled to prioritise proposals.

Our Research Support Office is integral to the administration of grant applications, ensuring that research is conducted according to appropriate ethical, legal and professional frameworks. The culmination of this process is a sign-off stage by HoDs or Deans which covers an on-line

checklist of risk, ethical and legal approvals. Ethical approval is further supported by a standing committee, with representatives from the discipline-specific level. These representatives routinely present at staff-meetings to raise awareness and disseminate policy relating to research and data.

Written codes of conduct support a research environment underpinned by *a culture of integrity* and based on good governance, best practice and support for the development of researchers. All staff complete the University online Research Ethics Training. Engineering research at Liverpool is conducted within a framework of Responsible Innovation that uses management-, peer- and public-review processes fostering creative research that is socially desirable and undertaken in the public interest. Representatives from Engineering (AKHTAR) sit on the Faculty Ethics Approval Committee. All departments within UoA12 operate Industrial Advisory Boards which provide a forum for benchmarking with professional standards such as IET, IOMMM and IMechE.

Section 2. People

2.1 Staffing strategy

In the current assessment period, Engineering disciplines have experienced a large increase in student numbers, which has facilitated the expansion of our academic research staffing (from 53 to 69 for CEID and MMA; and from 23 to 35 for EEE). This expansion has provided the opportunity to strengthen existing, and initiate new research areas (aligned to research strategy objective S3) whilst addressing the researcher demography, as well as diversity and inclusivity.

A sense of this is represented by the range of demographic information shown below which shows a significant percentage increase in female staff from 8.6% in 2013 (UoA13 and 15) to 19% in 2020 (UoA12).

Age distribution of Engineering academic staff; Median = 40-49 age range.

Age (%)	22-29 years	30-39 years	40-49 years	50-59 years	60-69 years
UoA12	2	32	30	19	7

Nationality and Ethnicity of Engineering 1A staff. RoW – "Rest of the World"; BAME – "Black, Asian and Minority Ethnic".

Nationality (%)	UK	EU	RoW
UoA12	53	26	21
Ethnicity (%)	White	BAME	Other
UoA12	60	33	7

Increase in percentage fraction of female 1A FTE's in UoA12 from 2014 – 2020

	2014	2015	2016	2017	2018	2019	2020
UoA12 Total 1A FTE	74	79	83	86	91	91	93
Percentage Female	14%	14%	14%	16%	16%	18%	19%

Ninety seven percent of our Category A eligible staff have open-ended employment contracts.

Our staffing strategy is aligned to the objective S2 to increase interdisciplinary research, consistent with an increasing emphasis on cross-disciplinary collaboration, crossing boundaries of schools and faculties, and creating a critical mass of researchers in areas with significant societal impact. This includes an emphasis on growing and supporting the development of our engineering academics. The staffing strategy for this REF period has had a strong focus on the development of Early Career Researchers and succession planning through promotional appointments aligned with the three overarching research objectives.

An example of developing our cross-disciplinary staffing is the Virtual Engineering Centre, established in 2010, which now has 22 staff, incorporating academics in Engineering, Computer

Science, Mathematics, Physics and Psychology. The multi-disciplinary nature of the team has strengthened the capabilities of VEC to become an award winning digital innovation centre, supporting the adoption of digital technologies to solve complex industrial problems and has supported growth in academics winning grants in these areas (see Section 3).

2.2 Engendering equality and diversity

Recruitment policies. To eliminate unintended bias and encourage more applications from applicants with protected characteristics such as disability, the "two-ticks scheme" is used across the Engineering departments during recruitment, and afterwards, ensuring retention, training and career development of employees. Similarly, statements committing to the promotion of gender equality and diversity are used in the recruitment process.

Our recruitment strategy for academic and research staff has a global reach, which is supported through HR recruitment mechanisms and policies. Consequently, our research community is truly international and ethnically diverse, as shown in 2.1 above.

In addition, the following actions have formed part of our common recruitment practice since at least 2014, and have contributed to our success in addressing gender imbalance:

- Appointments are advertised with the possibility of flexible working
- Every interview panel has at least one female member and one from another School.
- Our current practice mandates at least one female candidate on the short-list for each post.

UoA12 departments CEID, EEE & MMA have Athena Swan Bronze awards and ILCAMS was awarded Silver in 2017 in recognition of initiatives to identify gender under-representation; remove unintended bias; and embed principles of equality and diversity in our practices. As an example of our leading female academics, WILLIAMS (pictured right) was identified as one of the UK's most inspirational scientists and honoured at a reception at the House of Commons, where she was presented with an EPSRC "Recognising Inspirational Scientists and Engineers" (RISE) Award to celebrate innovation in engineering and physical sciences. Also, in 2018 BLACK was named as one of the Top 50 Women in Engineering (WE50).

Committees and Networks: All our governance committees are gender balanced. Examples of lead female roles include MITROVIC who is School Director of PGR and BLACK who chairs LivWiSE (Liverpool Women in Science & Engineering) which is just one example of opportunities open to staff to get involved in Diversity and Equality. Other University wide initiatives, promoted to UoA12 staff, include the BAME Staff Network, open to all University staff who identify as Black, Asian or from an Ethnic Minority, the Disabled Staff Network, which is a forum for consultation and discussion of University policy affecting staff with regard to disability issues, raising awareness of disability issues and providing support to disabled staff across the University and the LGBT Staff and Postgraduate Student Network, which is open to all staff and postgraduate students who identify as lesbian, gay, bisexual and/or trans.

Cover and support for parental and adoption leave: Our staffing policy supports formal flexible working following a period of maternity or adoption leave in recognition of continuing caring responsibilities. All UoA staff who have taken parental leave during the past five years have returned to work. This 100% retention rate, which gives confidence in our procedures for supporting staff returning from parental leave. For example, ZHU returned from maternity leave in 2017 with flexible hours and 50% FTE arrangement for six months, in order to provide care for her twins.

Support for staff with disabilities: A range of measures have been taken to facilitate the needs of staff with a range of different disabilities.

Characteristic	Without disability	Disability	Information withheld
UoA12 (Cat. A)	93.5%	2.2%	4.3%

In terms of physical environment, all buildings for Engineering researchers across the departments have been augmented by the installation and updating of access ramps, lifts alarms and facilities for visual and hearing impairments. All buildings now have vehicle parking for drivers with disability. Renovation of laboratory space and meeting rooms has considered aspects of access, working heights telephone and IT equipment. Our accommodation is classified as 'full access to building or access to a majority of public areas' under this scheme.

Equality and diversity considerations in the construction of this REF submission. Every element of the UoA 12 REF submission was overseen by a group consisting of a gender and ethnically diverse composition, compliant with both University and Faculty procedures and Codes of Practice. Research Outputs were identified by category A individuals annually, assessed by two reviewers independently. Subsequently, a moderating panel, comprising of male/female and ethnically diverse staff, reconciled the output ratings and written views covering aspects of originality, significance and rigour. The final output selection for UoA12 was made by a cross-departmental group following the protocol developed by the Faculty and University. Impact cases were selected from a Faculty-held repository which was used to collect examples of impactful research. Throughout the REF period, academic staff were given the opportunity to submit potential impact cases which were reviewed, by a peer-to-peer process with impact leads from other UoA's. This Environment statement was developed by a working group consisting of Heads of Schools, Heads of Departments and departmental REF-leads.

2.3 Staff development strategy

Our strategic approach to the development of staff at all stages of their careers aligns with the 3rd strand of our impact strategy (Recognition I.3) where we recognise and reward impact as an important feature of an academic's role and in this REF period we have strived to provide mechanisms to support the career development of all staff. Our approach to enabling impact and growth through our staff development strategy includes:

Induction and Mentoring, All staff have an induction which covers orientation with local procedures, Health & Safety practices and IT resources. New academics complete teaching training, leading to a Certificate of Professional Skills (CPS) including workshops covering diversity and equality training. All new staff also complete an obligatory training framework, consisting of an online programme of modules including GDPR, data security and leadership & management.

Early Career Researchers: We operate a policy of appointing a senior academic as a mentor for each early career appointment. Newly appointed ECRs are assigned mentors to assist them to successfully transition into established academics. Mentoring sessions every 4-6 weeks help to identify any issues or infrastructural needs (equipment, laboratory space etc.) as well as help with proposal writing, identification of key conferences and journals, introduction to key contacts in their research communities, cross-disciplinary collaborations, and industrial links.

We encourage ECRs to engage with the University's Early Career Researchers Forum which provides ECRs with a network for understanding their experiences and needs, with feedback to local and Faculty-level management. An example raised by the forum was a request for further training to help PDRAs transition to a permanent position. The Forum also provides a route by which ECRs can influence Faculty policy, for example by improving the induction and mentoring process. Career development and training for ECRs include: allocation of PhD studentships to first grant awards; pump-priming funds, in addition to initial seed funding and the mentoring programme. Fellowship applications receive further support, such as mock interviews. A policy has been adopted to enrol PDRAs who successfully obtain a fellowship into tenure-track positions. Continued investment in the tenure track fellow programme since 2013 has led to more than ten ECRs becoming part of the academic cohort [e.g. CHRISTIAN and ZHANG].

We identified that posts available to our postdoctoral fellows at Lecturer and above (Grade 8) were relatively limited, creating a “bottle neck” in academic careers for all postdoctoral scientists (Grade 7). This career transition point is the on-going subject of a number of focus groups both locally and nationally. A number of PDRAs from UoA12 are engaged in a new £4.4M funded project called Prosper awarded in 2019 by Research England and led by the University of Liverpool in partnership with the University of Manchester and Lancaster University, to support future career development prospects of PDRAs.

Support for established staff: Throughout the UoA, emphasis is placed on the importance of the PDR. The process is underpinned by local workload models, which aim to balance teaching, research and management activities, whilst providing transparency and fairness. Progression is core to our annual reviews and all PDRs include discussions on plans and ambitions, progression opportunities and challenges in undertaking research, and training/support requirements.

Sabbatical and research leave is available for a period of one semester within a five-year period, and academics returning from maternity, adoption, shared parental, additional paternity, extended carer's, or long-term sickness leave are encouraged to apply for one semester of sabbatical leave to help them re-establish their research or scholarship activity. For example, YAN utilised a year-long sabbatical leave opportunity to develop a REF2021 impact case targeting the removal of SF_6 from electrical switchgear.

All members of staff contribute to regular research group meetings, and additionally the departments host "research theme" workshops designed to encourage and foster cross-disciplinary research, in direct support of our objectives S2 and S3 to increase interdisciplinary research and increase orientation of research infrastructure towards addressing regional, national and international research themes and challenges.

As referenced in 1.4, support for staff developing significant impact activity has been a focus of our staffing strategy, through providing time, money, space and sabbatical opportunities and the UoA has actively participated in a suite of impact training delivered centrally though our annual ‘Making an Impact’ series, which has been running since 2018. In 2018, 196 participants from UoA12 engaged in intensive development activities across 28 sessions, including 1:1 surgeries, panel Q&As, facilities tours, keynotes, workshops, micro-seminars and showcases. These are designed to foster conversation and interaction, in support of the University’s ambitions for a borderless research community. In addition, the University has an extensive on-line training program of Continuing Professional Development, for all staff cohorts covering a wide range of topics such as Ethics, Equality and Diversity, and Recruitment and Selection. The Centre for Lifelong Learning offers a development program for research staff on career mapping.

Mentoring and support strategies are in place, including opportunities to meet with peers, reflect on developmental needs and identify personal targets through the PDR process. Help is available from Professional Services (PS) colleagues both in faculty and centrally to identify and progress grant funding opportunities. Regular workshops are also organised in collaboration with funding bodies (e.g. EPSRC and RAEng). An example is the internal funding and PS support offered to BROWNING to organise a networking event in 2018 with academics involved in energy storage from across the UK. This support contributed to a successful £1M funding proposal led by UoL under the ISCF Battery Challenge.

Wellbeing. All Departments are committed to supporting the health and wellbeing of our staff and students. Positive mental and physical health is promoted via a range of support services including: a confidential counselling and information service available to assist with personal or work-related problems; mindset self-coaching; Occupational Health Services; access to high quality sports facilities and recreational meeting places; social events; and support for charity fund-raising events. This includes ‘Liv to Give’ the University’s Staff Volunteering Framework. Every member of staff can have up to three paid days per academic year to volunteer. The scheme also supports fundraising, charities chosen by staff and donation points for charitable appeals.

Support for potential leaders is initiated through our annual Personal Development Review (PDR) process and informal mentoring meetings with senior academics also help prepare for future leadership roles. The UoA has benchmarked its internal criteria for academics’ promotion to

reflect the University's policy, which considers research, teaching, and administration, as well as impact performance. An example of our staffing strategy and development of potential leaders is WALSH who joined as an ECR (lecturer) in 2010 and has subsequently developed into an internationally recognised leader in Plasma Microbiology. He has won a five-year EPSRC Healthcare Technologies Challenge Award, one of only nine announced in the House of Commons. The award has led to the establishment of a new EPSRC Centre in Plasma Microbiology to develop novel biomedical devices.

Succession planning. In line with the strategy objectives, in particular (S.3.Increased orientation of research infrastructure) a number of strategic appointments have been made with succession planning in mind. In Engineering Design, a new Chair in Industrial Design (SCHAEFER), together with academic appointments (NICKPOUR, DI SARNO, MILISAVLJEVIC SYED, HAN) has stimulated new research in Cloud-based Design and Manufacturing and Cyber Physical Systems for Product Creation and Production Engineering and the appointment of two new Chairs in Aerospace Engineering (CADOT and THEOFILIS) has been coupled with upgrading wind tunnel test facilities (£1.5M) to support future research in modelling and simulation of aerodynamic ship design and helicopter operations.

2.4. Developing the talent of our Postgraduate Research Students

Across Engineering we have a vibrant and diverse community of Postgraduate Research Students. The table below shows the numbers of graduating PGR's within the period.

Numbers of graduating Postgraduate Researchers within the period							
	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20
Graduating PGR's	30	46.9	39.2	52.79	62.9	65.8	57.4

Our postgraduates are key to the vibrancy and future vitality of the research culture within the unit and we provide a well-equipped, well-resourced research environment for our PGRs that encourages collaboration across disciplines and supports learning, research and personal skill development.

Our strategy for PGR internationalisation and diversity includes the development of research collaborations with Universities in Taiwan (National Tsing Hua University), Singapore (A-Star) and China (XJTU, Huazhong University of Science and Technology), through the joint supervision of PhD students, who obtain a PhD award from Liverpool and the overseas host institution. The dual degree is based on a '2+2' model, which can be two years at Liverpool followed by two years overseas, or vice versa. As well as Dual PhD Degrees the University also has an established relationship with XJTLU - our Chinese campus. These students have supervisors from both XJTLU and Liverpool and spend a minimum of 3 months in Liverpool during their 2nd year of study. As part of UK-Jiangsu Initiative, we host PhD students from China for up to 6 months and ECRs for up to 12 months. In 2019, we hosted 40 PhD students and ECRs. In terms of gender diversity, the percentage of female PGR students is now at 19.5%, which is an increase from the start of 2014 (15.6%) and reflects our staffing strategy to focus on increasing equality and diversity across our departments.

A significant proportion of the PGR students across the Engineering disciplines, benefit from specific training and development provided within the 4-year programmes of several UKRI Centres for Doctoral Training including:

- Doctoral Training (CDT) on Quantification and Management of Risk & Uncertainty in Complex Systems & Environments;
- EPSRC CDT in New & Sustainable Photovoltaics;
- EPSRC CDT in Additive Manufacturing and 3D Printing;
- EPSRC CDT in the Science and Technology of Fusion Energy;
- EPSRC CDT in Distributed Algorithms (UoL leads);

- EPSRC Next Generation Nuclear Centre (NGN) for Doctoral Training ("GREEN" from 2019).
- Leverhulme Research Centre for Functional Materials Design;
- DTC in Dependable Autonomy Systems is part of UN-Jiangsu initiative (UoL leads);

The Liverpool Doctoral College forms the basis for all doctoral training and development across the University. Student monitoring and training support is provided through "Liverpool Life" which is a web-based portal for students to maintain and access records. All postgraduate research (PGR) students across the UoA, maintain an online record of their research progress, supervision, as well as a record of their professional development. Training modules are offered based on a professional development plan (PDP) developed in consultation with their supervisors, to help them identify the training needs to advance their research and career ambitions.

We also encourage wider networking within the sector, for example the annual Postdocs in Nuclear Energy meeting (PiNE) was hosted at UoL in 2019. PiNE offers the opportunity for post-doctoral or equivalent level researchers to get together in an informal environment, share their work and learn what else is going on in the nuclear research community.

PGRs are encouraged to showcase their research. A pleasing example of success is WONG, pictured right (middle) who was awarded the Young Innovator award at the prestigious Institute of Engineering and Technology (IET) Innovation Awards (2019) for his research in 3D printing Quality Control. Also, CHANG was awarded a prestigious Chinese Government Scholarship for "Outstanding PhD Thesis for Self-Funded Students" in 2018 - one of only eight from the North West to win this award.

The Liverpool Doctoral College offers programmes to develop PGR skills enhancing Employability and Entrepreneurship. This links closely with the internationally recognised Vitae Researcher Development Framework, supporting the implementation of the Concordat to Support the Career Development of Researchers; the QAA Code of practice for research degree programmes; and the 'Roberts' recommendations for postgraduate researchers and research staff. This approach is augmented by a programme of annual career development workshops. We hosted more than 40 alumni in 2017, who provide careers advice to 150 students and PGRs. The alumni included graduates working with Airbus and Aston Martin, for example, shared knowledge on how to break into the engineering jobs market successfully. Industry and policy engagement is encouraged, for example Watson, a School of Engineering PhD student, was selected in 2020 to present his research to Members of both Houses of Parliament and a panel of expert judges, as part of the STEM for Britain event.

Our international alumni network provides positive female role models for PGR students, PDRAs and ECRs. Female alumni (e.g. Dr Helen Davock, Bentley Motors) have been invited back to meet PGR students and offer career advice, placements and endorsements. We also offer places on the Science and Technology Leadership Programme for final year PhD students.

Section 3. Income, infrastructure and facilities

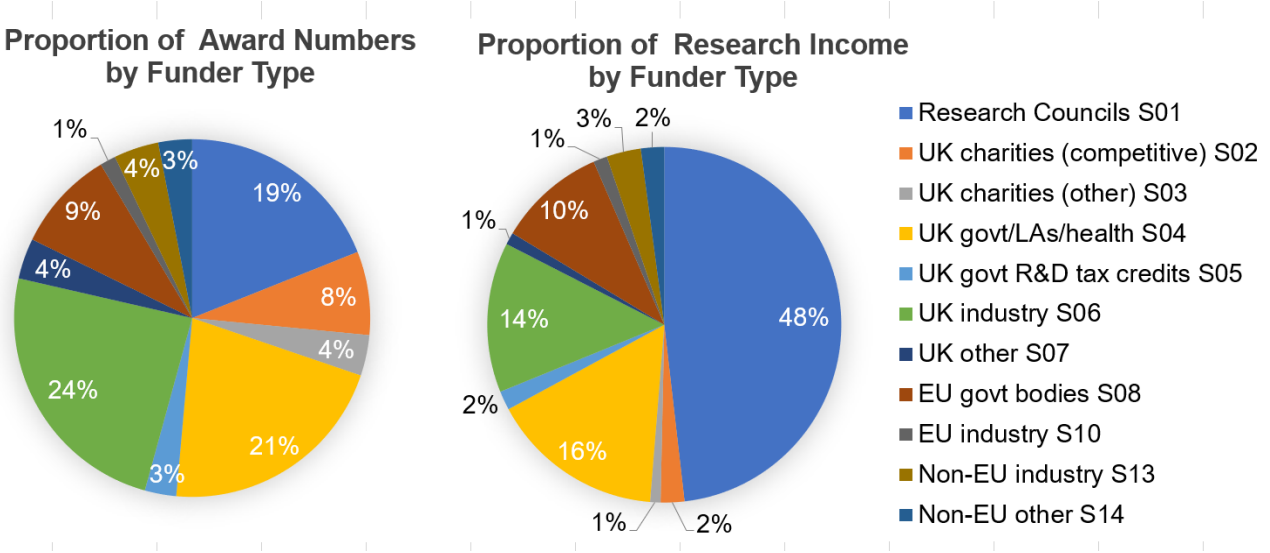
3.1 Supporting research income

In line with our overarching research objective S2 (to increase inter-disciplinary research), we have focused our funding sub-strategy over this REF period on the establishment of large research consortia and projects and increased engagement with funders and stakeholders. A summary of the sources of research funding during the REF period is provided below, illustrating the scope and distribution of funding sources.

Engineering researchers (PI and Co-I) have engaged in 462 externally funded research projects. The largest proportion of these (21% by number) were through the Research Councils (NERC, MRC, STFC and primarily EPSRC), with a total research income of £26.44M (48% of the total

value) for the University. One example of a larger project is the UKRI consortium "UK Robotics and Artificial Intelligence Hub for Offshore Energy Asset Integrity Management" (JUMP, EPSRC, £14.6M total project partnership). The total number of grant applications and the total value of research awards comes (on average £7.86M/year) from an increasingly diverse range of funders, as the diagram below illustrates. Our four largest sources of research funding are: Research Councils (48%); UK Government, Local Authorities and Health (16%); UK Industry (14%); and EU Government bodies (10%).

By value (£5.41M,10% of total), EU government funding has been a significant international research income source for Engineering. Examples in this REF period include an EU research consortium coordinated by TIMME within the "AEROGUST" project consortium (H2020-EU.3.4., €4.3M); DEARDEN and EDWARDSON collaborating with the EU H2020 project ENCOMPASS (€4,04M) and TU collaborating in the EU H2020 multi-national - multi-partner Innovative Training Network EUROPAH (€4M) on plasma processing of polyaromatic hydrocarbons.



External engagement with funders has been led by our faculty Executive PVC (Van der Hoek) who meets UKRI quarterly to review thematic priorities and future calls for research. A number of staff have been directly involved with EPSRC via their work on Strategic Advisory Teams (SATs), e.g. BLACK (Manufacturing the future), D'SA (Physical Sciences), WHITTLE (Energy), or as recognised Leaders, e.g. WILLIAMS (RISE Leader), PAOLETTI (RISE Rising star), POOLE (Established Career Fellow) and share information with colleagues.

Information on future calls is disseminated via our intranet, staff briefings and through targeted weekly research intelligence bulletins, which are sent via email by the School's Research Support Officer to targeted mailing lists, highlighting relevant funding opportunities and workshops etc. Staff members are encouraged to attend funder networking events.

We have established a program for inviting wider external stakeholders to visit campus. In 2019 KTN were invited to visit to campus to meet our researchers involved in AI and robotics, which subsequently led to the University being invited to have a stand at a national Robotics and Artificial Intelligence Industry Showcase, and also to engagement with a number of new industry contacts.

Internal engagement is also key. Representatives from UoA12 sit on the institutional theme steering groups, (digital theme is a strong example) where a coordinated approach provides a mechanism to identify strategic inter-disciplinary funding opportunities, the opportunity to initiate the right support needed to prepare funding bids and sets a framework for a robust selection processes and internal peer review of projects.

Members of UoA12 are also represented at the University Industry partnership meetings with Unilever and IBM, where strategic research funding opportunities are discussed.

The unit maximises internal funding opportunities to pump-prime research and knowledge exchange activities and impact generation. UoA12 has been awarded £1.18M through University-

managed EPSRC strategic funding call "Impact Acceleration Account" and internal Industrial Strategy HEIF funds. An example of success is WALSH who was awarded £21k ISCF internal pump priming funding in 2018 to work with Campden BRI to establish a new plasma measurement capability. The system developed using the funds has been used in three successful subsequent funding proposals to EPSRC and the European Commission, totaling over £900k.

An example of new project funding streams arising from our wider funder engagement is a Department of Transport funded project 'Shape-Pot' led by PAOLETTI applying the latest techniques in engineering to solving the ever-increasing issue of potholes via autonomous robotic repair tools.

Our engagement with EU funding is supported through our central Research Support Office and by financial assistance for researchers to attend EU briefing meetings, networking and resources for bid preparation. This approach has promoted successful outcomes in winning EU grants under Horizon 2020, Marie Curie networks and COST programs. A similar approach is taken to our engagement with international funds (ODA/GCRF), which are widely promoted across the unit and we have seen a growth in successful applications to this fund. In 2019 D'SA received funding for Point-of-use water filtration in India as part of a £650k UKRI GCRF award to UoL to deliver scalable solutions to issues faced by low and middle-income countries.

Future funding strategy

Linked to our forward strategy, under F1, we will look to maximise funding leverage to "Sustain and Grow" our research spaces, laboratories, facilities and equipment and build on the investment in areas such as the DIF. We will also target increased industrial collaborations as we continue to develop inter-disciplinary funding opportunities aligned to our "Civic and Global" objectives, particularly in areas where we have renowned research strengths, for example in digital and materials. This will include strengthening our local and regional relationships within Liverpool City Region, to support the COVID-19 economic recovery plans and leverage funding to initiate joint research initiatives that can focus on innovative research and impact aligned to the 'building back better' agenda.

We will also continue to invest in our early career researchers (F3), with a funding strategy that will ensure they continue to have the opportunities to apply for funding to take their research forward, taking equality and diversity fully into consideration.

3.2 Estate and Operational Infrastructure supporting research and impact

The unit has a range of specialist engineering research laboratories and research facilities. Engineering services include two workshops and 25 Technical Support staff. The Engineering Workshop services provide precision machining of most engineering materials. There is also a bespoke design service with full 3D modelling including instrumentation of discrete devices, strain gauge installation and motor controls. The Electronics Workshop provide a range of services to the Faculty of Science and Engineering for the development and maintenance of electronic equipment and prototyping of printed circuit boards.

Other facilities include the Daresbury campus, which houses facilities for working in laser technology, superconducting thin films, electron microscopy and virtual engineering. Engineering researchers are also located at the Cockcroft Institute, which is a partnership between the Universities of Lancaster, Liverpool, Manchester and Strathclyde, and the Science & Technology Facilities Council (STFC). The Institute is the national centre for accelerator R&D in the UK. In this context, CORNER (strategic SoE appointment to strengthen links with the Cockcroft) leads her work on the development of new laser sources for a number of applications in accelerator science, as well as on campus work within the Laser group.

The Albert Crewe Centre at Liverpool (iCAL) (BROWNING and MEHDI) is a leading multi-disciplinary research facility for the characterisation of materials by electron microscopy and spectroscopy. The facility is open to the University of Liverpool research community and collaborative academics from external institutions worldwide.

In late 2015, ILCAMS moved into a new £35M purpose-built facility (The William Henry Duncan Building) on the main University Campus in Liverpool City Centre, bringing together academics

from a number of sites across the university campus. In addition to the upgrade to state-of-the-art laboratory facilities and office space the new building brought together research groups and students who had previously been separated across 9 different buildings and 70 individual laboratories into a single building with 3 large, bespoke laboratories.

The Materials Innovation Factory (MIF) provides an open-access facility, integrating materials research with analytical, computational and robotic equipment to accelerate materials development, as well as a range of characterization facilities. The MIF is supported by a strategic joint SoE-MIF appointment (GARCIA-TUNON). These facilities are exploited by both this appointment and other Engineering researchers (BLACK, CHALKER, POTTER, PAOLETTI). The MIF also provides a physical home for the Leverhulme Research Centre for Functional Materials Design (CHALKER, POTTER, PAOLETTI, GARCIA-TUNON), and collaborates through the Leverhulme Research Centre for Functional Materials Design (Lead Cooper FRS, Chemistry, £10M, 10 years, Co-I's CHALKER and PAOLETTI). The Leverhulme Research Centre is driving a design revolution for functional materials at the atomic scale by fusing chemical knowledge with state-of-the-art computer science in a world-leading interdisciplinary team. The MIF facilities underpin the engineering materials research in water-based formulations for Additive Manufacturing; 3D-printing of functional materials; thin films for renewable energy; and robotic manipulators for automated synthesis.

The University and National Nuclear Laboratory (NNL) committed to a strategic partnership in 2014 aimed at developing international research on nuclear power generation. The partnership provides staff and students access to NNL's Central Laboratory at Sellafield where they can perform experiments on radioactive material. The University also has a Memorandum of Understanding with The University of Manchester that provides access for Liverpool staff and students to the Dalton Cumbria Facility, which includes an accelerator and Cobalt source. SoE (DENNIS, WHITTLE) also forms part of the Centre for Innovative Nuclear Decommissioning (CINDe) which was established in 2017, led by the UK National Nuclear Laboratory (NNL) working in collaboration with Sellafield Ltd (SL), the University of Manchester, Lancaster University, the University of Liverpool and the University of Cumbria and is based at NNL Workington, Cumbria.

The new Digital Innovation Facility (DIF), within the University of Liverpool's city centre campus will be a centre of excellence in simulation and virtual reality, bringing together complementary areas of research of autonomous systems, distributed simulation and immersive visualisation, robotics and engineering. This is a purpose-built collaborative research and development environment offering the ability to foster and grow businesses, focusing on three priority sectors where Liverpool City Region has competitive advantage - advanced manufacturing and engineering, low carbon energy, and digital industries - as well as other significant growth sectors including health. Within the DIF initiative, MARSHALL is establishing a new multi-sensory immersive reality facility; and MASKELL is establishing a dedicated space for working closely with Dstl. The DIF will also house the maritime sector's Digital Accelerator, which is a new collaboration with Mersey Maritime, focused on delivering MarRI-UK - the Department of Trade's maritime research and innovation strategy to 2050.

At Faculty level, Shared Research Facilities (SRFs) support quality research and impact alongside expert knowledge and support. The Faculty has made significant investment, with a dedicated budget of approximately £500k assigned to the purchase and maintenance of equipment each year. The Shared Research Facilities are free at point of use for university staff and students to ensure that access to funding is not a barrier for use of equipment for research and proof-of-concept activities. They are governed centrally by a Faculty-led Steering Group and access is via an online booking system. Both mechanisms are intended to promote transparency and fairness, supporting the research needs of researchers at every level.

We benefit from a range of information and computing resources. In particular, two subject-specific Librarians support colleagues across UoA12. In terms of online resources: our on-campus Computing Services currently support four parallel computing, Beowulf clusters with a variety of hardware and software configurations. From 2018, two parallel Linux clusters form the basis of the main HPC resources. In addition, researchers are able to apply for time on the

national ARCHER service, as well as on one of the EPSRC Tier-2 systems. Off-campus, engineering research is also performed at the Hartree Centre.

To support Aerospace Engineering, strategic new appointments were made at chair level (CADOT, THEOFILIS) and lectureship appointments (FICHERA, SOLDANI). We have also made a major investment (£2M), funded by an endowment, in refurbishment of our wind tunnel facilities and procuring the latest state-of-the-art laser instrumentation leading to the opening of the 'Bibby Aeronautical Laboratory' in late 2019. Aerospace engineering is also well supported by world-leading flight simulation facilities: two full motion "turnkey" flight simulators (Heliflight and Heliflight-R) which are reconfigurable for flight dynamics engineering and training applications.

3.3 Impact and Entrepreneurship Support

Engineering researchers are supported in the process of securing IP protection for their research. Over the last 20 years Liverpool engineers have filed more than 50 patent applications, covering aspects of new material, novel manufacturing processes and innovative devices. Support is received from the Intellectual Property Commercialisation team. Examples in UoA12 include:

- Q-Technologies, a start-up by TAYLOR, develops and supplies innovative micro and miniature mass spectrometry systems. The company's developments include an artificial sensor to complement the work of sniffer dogs at border checkpoints; an in-water mass spectrometry system used in aquaculture; and work for the National Nuclear Laboratory.
- Fusion Implants, started by Sutcliffe and Jones, is a start-up company, based within the University, which has developed a surgical implant to cure lameness and restore mobility in dogs. Fusion Implants produces veterinary implants using 3D printing techniques to manufacture porous titanium parts, which allows the animal's bone to grow into the implant.
- The start-up, Robitiz3D led by PAOLETTI and FISCHERRA, is developing fully integrated, semi-autonomous robotic systems for the detection and repair of defects in road surfaces.
- Meta Additive, started by BLACK is a spin out developing a chemical approach to binder jetting 3D printing, based on high solid loading binding agent formulations.

Since 2013, a dedicated Consultancy Team provides an end-to-end consultancy service managed via an online approval and facilitation system (CONSULT) which automates requests for approval and Professional Services support, enabling reporting and recognition of activity. UoA12 has delivered £479k value consultancy projects in the REF period, with key research users in the nuclear, renewable energy and healthcare sectors.

Section 4. Collaboration and contribution to the research base, economy and society

4.1 Research collaborations, networks and partnerships

Engineering academics have benefitted from various strategic global partnerships. A sense of this is given by the range of international institutions and organisations we have worked in the period.

4.1.1 National and international collaborative networks and partnerships

International - In terms of global research partnerships, we have successfully collaborated with X'ian Jia-Tong Liverpool University (XJTLU), placing us at the heart of key research partnerships such as the UK-Jiangsu 20+20) World Class Universities Initiative. Following a 2017 dialogue between the UK and Jiangsu province, UoL was elected to lead a 5-year programme to strengthen research collaborations between UK and Jiangsu academic institutions. MARSHALL is the UK lead and UoL are the current secretariat of the UK-Jiangsu "World Class Universities" initiative (2018-23) involving 20 UK and 20 Chinese universities, which has overarching themes of Advanced Manufacturing, Environmental Engineering, and Healthcare.
In addition, Liverpool (MITROVIC, HALL) is a founder member of the EPSRC Network e-futures and a founder member of SiNANO which has 22-member institutions and is recognised by European Commission and Industry as the leading European Institution representing the Nanoelectronics Academic Community.

Under this initiative a joint Doctoral Training Centre in Dependable Autonomous Systems (DPAS), was established and provides tailored training programmes for PhD students from both parts and supports in-depth collaboration between the participating Jiangsu and UK Universities. PhD

students from the UK partners (UoL, York and Queens Belfast) visit counterpart universities in Jiangsu (Southeast University, Soochow University and Nanjing University of Science and Technology) for a year and vice versa. Initiatives under this scheme include the opening of Jiangsu industrial science parks, giving UK institutions access to >3000 companies in Changzhou park.

The global reach of our international collaboration is illustrated below from Scopus - SciVal.

Numbers of International Collaborations shown in circles by Region

National - Through a strategic partnership with IBM, MASKELL is leading a £2.5M EPSRC-funded "Big Hypotheses" project (2018-2023) which has attracted £1M of in-kind contribution from the company. IBM's interest in this project and in Distributed Algorithms has led to a Joint Study Agreement with the University of Liverpool. This UoL-IBM strategic partnership means that, for example, PhD students from EEE are seconded to IBM for 3 months and have access to their high-performance computing facilities in the US. In addition, MASKELL contributes to inter-governmental collaboration on behalf of the UK and associated with TTCP, NATO and classified panels.

In collaboration with the National Oceanography Centre, RALPH leads the Dstl / EPSRC funded £1.3M project "Bayesian Localisation in the Underwater Environment (BLUE)" which is focused on developing novel solutions to the signal processing challenges encountered in underwater sensing; covering sensor data fusion, automated tracking and the interpretation of short-lived signals in highly cluttered environments.

Our strategic partnership agreement with the National Nuclear Laboratory (NNL) provides access to NNL's Central Laboratory at Sellafield. Another partnership with the University of Manchester provides access to the Dalton Cumbria Facility, including an accelerator and a cobalt radioactive source.

4.1.2 Enabling and facilitating collaboration

Strategic support to promote both international and national collaborations is achieved via mechanisms including:

- Financial support for strategic travel costs;
- IT infrastructure and physical space for hosting networking, workshops and conferences;
- Ring-fenced time for research;

- Longer-term sabbatical leave;
- Faculty and University-level support for strategic partnerships
- Direct funding (e.g. Knowledge Exchange and Impact vouchers), PhD studentships with CASE partners
- Part-time working arrangements for colleagues to work in the industrial environment.

The sabbatical leave policy has a strong focus on the development of research collaborations and partnerships. For example, YAN used a one-year sabbatical to develop research collaborations with Xian Jiaotong University (XJTU) and partnerships with Pinggao Group. These included a joint MPhil and PhD project to combine our strengths in tackling the fundamental challenges in developing low carbon technology for power system protection. During his sabbatical in Pinggao YAN has trained design engineers in switching theory and on the use of Liverpool's circuit breaker design optimisation tools. This has helped advance the technology transfer in relation to circuit breaker design at Pinggao, with a £100M annual turnover in 2019 from the new products designed using Liverpool's technology. Arising from this, an impact case has been developed. "Developing a comprehensive simulation tool to aid the digital design of high voltage circuit breakers".

Internal funding schemes such as KE&I and EPSRC IAA vouchers have enabled collaborative partnership projects with a range of external stakeholders. A new scheme within this period included the award of 11 knowledge exchange vouchers (£70k) to work specifically with locally based SMEs based in Sensor City and in Daresbury Innovation Park.

4.2 Developing impact through engagement with key research users, beneficiaries or audiences

Engagement with industrially relevant R&D is core to the engineering research ethos at Liverpool. This is supported through our industrial advisory boards; collaborative and directly-funded research; consultancy, KTPs, technology transfer and licensing and coordinated engagement with Knowledge Transfer Networks and Innovate UK. An example of this is the KTP Partnership with UltraVision (ELSHEIKH) was graded by a panel of independent assessors as Grade A (Outstanding). The project (March 2014 to December 2017), developed state-of-the-art contact lenses for people suffering from vision loss due to irregular corneas. A suite of software codes was built to deal with all types of distorted corneas. This now allows any corneal profile that can be measured by an eye topography device to be modelled in our advanced FE software. The outputs obtained were designed to be flexible enough to be used for developing all contact lenses produced by the company.

Industrially sponsored research (UK, EU and non-EU) is our second largest combined research income (£9.91M, 18% of total), spanning across industry sectors from energy (National Grid Company ltd, Henan Pinggao Electric Co. (China), Hyosung Corporation Power & Industry System (Korea), Aeternum LLC (USA), Thales (France), TNB Research SDN BHD (Malaysia), Johnson Matthey, C-Tech Ltd, GE, HIDEN Analytical, Plasma Clean Ltd, Unicorn Power Ltd, Sellafield and NNL, to defense (BAE System, QinetiQ, National Nuclear Laboratory, USA Arm, Raytheon (USA), MBDA UK Ltd., Riskaware Ltd., etc.), and other sectors (Dyson, Pfizer, Unilever, Saras Technology Ltd., etc.). Other research beneficiaries include global-scale corporates (e.g. Amec Foster Wheeler; Delphi Electronics; HR Wallingford; Jaguar Cars; Jaguar Land Rover; Nanoco Technologies; Qinetiq; Procter & Gamble; Schlumberger; Unilever) to small-medium enterprises (SMEs) (e.g. Alphasense Limited; Fusion Implants; Photek Ltd; Pegasus Chemicals Ltd).Other key research users include UK Government and the NHS.

The examples below demonstrate our broad range of engagement and relationships with key research users and beneficiaries, addressing technological needs:

Healthcare Sector & NHS

- One particularly notable area is Additive Manufacturing (AM) which has been significant within the REF period. TATLOCK has worked on metal powder feedstock materials with Carpenter-LPW; AM processing equipment with Renishaw; and end-users including

Stryker Orthopaedics and Fusion Implants – a spin-out from the University of Liverpool. Stryker has featured in one of our impact cases.

- Sensor City awarded a £3.5M grant (DCMS 5G Testbed and Trials programme) to investigate the opportunities of 5G community Wi-Fi in health and social care, helping to bridge the digital divide across deprived communities in Liverpool City Region.
- CEID (NICKPOUR) has developed strategic links with Alder Hey Children's NHS Foundation Trust in the development of child-centred design frameworks for future paediatric assistive mobility. This has included two Hugh Greenwood Legacy funded projects focused on interdisciplinary personalised health.

Government / Defence Sector

- MASKELL's Signal Processing group has a number of ongoing interactions with Dstl who are currently funding the development of demonstrators that will be used in two UK MoD intelligence sites, one related to maritime security (with wider links to, for example, NCA, Border Force, Police, Security Services etc.) and one related to strategic intelligence.
- MARSHALL has expanded communications research via establishment of the Advanced Network Research Group that specialises in Trust and Physical Layer Security IoT, and defense related research into directional MANETs (with Dstl and Plextek).

Aerospace Sector

- Research in the field of Aerospace has engaged with Airbus; BAE Systems; and GE Aviation Systems. For example, the Virtual Engineering Centre (VEC), has worked in partnership with BAE Systems, to develop a Virtual Engineering Simulation Laboratory (VESL) for the integration, test and generation of evidence for certification of components of Autonomous Remotely Piloted Aircraft Systems.
- RALPH was co-I on the "Growing Autonomous Mission Management Applications (GAMMA)" project, funded by the Department of Business Innovation and Skills to transfer technology and software expertise to assist SMEs in the emergent UAV/Drone industry, via the North West Aerospace Alliance (NWAA) and BAE Systems (£621k).

Cross-Sector

- Research activities in novel plasma technology (WALSH) for environmental control and food hygiene to sterilise polymeric packaging materials at the point of fill, have led to strategic engagement with leading UK companies (*e.g.* Sainsbury's, Dyson, Unilever & Olympus). Initial work funded by a UoL Impact Acceleration Award has resulted in the co-development of novel plasma-based technologies (*e.g.* EPSRC, Challenging Engineering Award, £260k). The technology has been integrated within a single lane packaging machine and the prototype is now being assessed by an independent testing body with a view to achieving FDA approval.
- The work of SHEN's group on non-destructive analysis of coatings using terahertz imaging and optical coherence tomography has attracted interests from major international companies who have since provided either in-kind support (test sample of car paint panels from Land rover (UK); test sample of Surface laptop coatings from Microsoft (USA), trial measurement facilities for on-site in-line measurement at Bosch (Germany)), or cash support (funding from Pfizer (UK) and Unilever (UK) for feasibility studies).
- MARSHALL's research into network architectures for multi-sensory communications ('Creating a Stink - Investigating Olfactory Transport Streams' (£492k), 2015-18 and ('Context Aware network architectures for Sending Multiple Senses (CASMS)' £1.3M, 2017-2022 (with UCL, BBC and Virtalis) has subsequently led (with additional internal UoL matched funding of £150k) to the establishment of the Centre for Multi-sensory Communications (CMC - based in the DIF) that now offers unique world-class facilities

to investigate the introduction of olfaction (smell) as well as other sensory channels into next generation networks and virtual environments.

- HOETTGES was Co-I on a £1.15M UK Space Agency funded project using microgravity as a model for accelerated skeletal muscle ageing. This project studied Myotube muscle cells within the confines of the KUBIK facility onboard the International Space Station.
- PATTERSON is the academic lead of a £2.9M initiative, funded by BEIS with Amec Foster Wheeler, for a UK Digital Reactor Design partnership to improve the design and build of new nuclear reactors, with optimised operating lifetime performance. Other partners include the National Nuclear Laboratory, Rolls-Royce and EDF Energy.

4.3 Contribution to the sustainability of the discipline

In the context of learned societies and the professional bodies, we make significant contributions to the visibility of the engineering disciplines and their importance in formulating policy and governance.

- *Fellows of the Royal Academy of Engineering (FREng):* Professors Rachel WILLIAMS, PATTERSON; Emeritus Professor ESCUDIER; Emeritus Professor GOODHEW; PADFIELD FREng; Visiting Professor TAYLOR (FREng) from the National Nuclear Laboratories (NNL).
- *Fellows of Institute of Engineering and Technology (FIET):* MARSHALL, HUANG, SHEN, TAYLOR, HALL, MASKELL, RALPH, SPENCER.
- *Fellows of the Institute of Mechanical Engineering (FIMechE):* PATTERSON;
- *Fellows of the Institute of Materials, Minerals and Mining (FIMMM)*: AKHTAR; CHALKER; Emeritus Professor TATLOCK; Professor ZHAO.
- MASKELL has been elected to be president of the International Society for Information Fusion for the 2021-2022 term.

UoA12 also contributes to sustainability of the discipline through our research addressing national priorities and grand challenges, for example: BROWNING study commissioned by The Faraday Institution, from which the recommendations are a foundation of the Faraday Battery Challenge, aiming to ignite a revolution in battery research and accelerate the move to electric vehicles (EV); MASKELL contribution to 'Big Data' (one of the Government's eight great technologies) focuses on developing ground-breaking, translatable algorithmic solutions across multiple sectors in both industry and government; WHITTLE's contribution the ambitious N8 Net Zero North (NzN) initiative will connect science assets, skills providers, and businesses to forge a green recovery from Covid-19, putting the UK and the North at the forefront of the global drive for net zero carbon.

Other wider contributions to sustainability include our schools outreach programmes, e.g. 'Headstart into Aerospace programme', where each year we host school students across the UK, showcasing exciting opportunities available in aerospace engineering.

4.4 Wider influence, contributions to and recognition by the research base

Contribution to Editorial Roles:

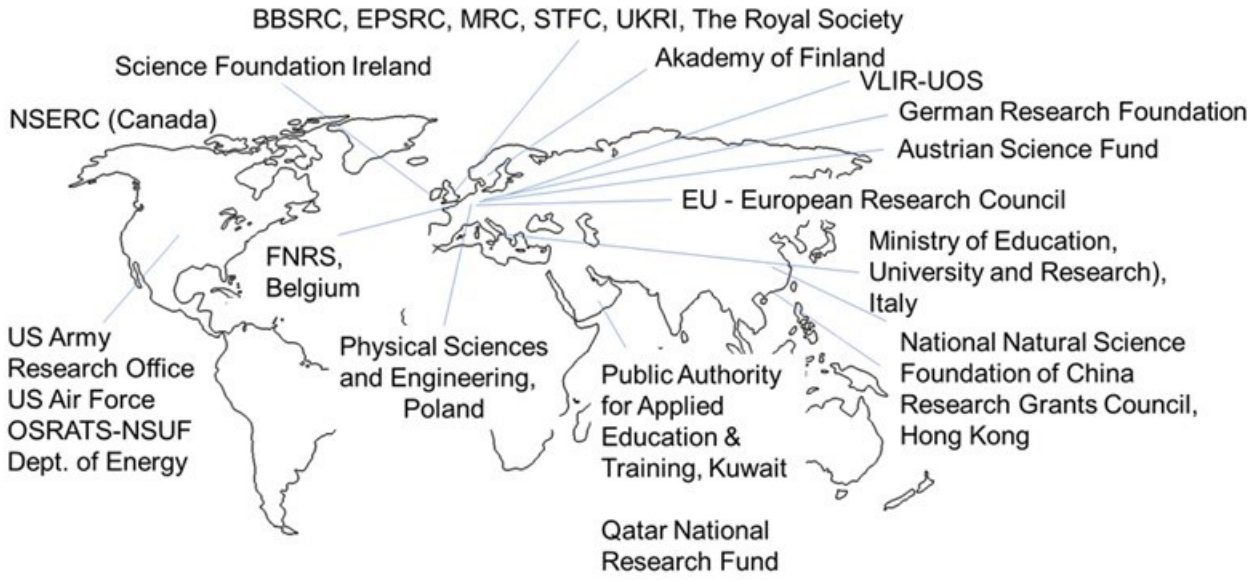
We are engaged with a range of peer-review journal editorship.

Some notable examples : ***Editor in Chief / Editorial Board level*** are BROWNING - Editor in Chief: Advanced Structural and Chemical Imaging (Springer Open Access Journal); Editorial Board: Micron, J. Microscopy; BERTOLA - Editorial Board member, Advances in Colloid and Interface Science ; Editorial Board member, Atomization and Sprays; DENNIS - Editorial board member of Heliyon; EDWARDSON - Editor of Advances in Aerospace Engineering open access journal (2014-2018); MERK - Member of the academic editorial board of PLOS ONE; MOTTERSHEAD - Editor-in-Chief: Mechanical Systems and Signal Processing; Editorial Board: International Journal of Mechanical Sciences; OUYANG - Deputy Editor-in-Chief of Journal of Sound and Vibration; Editor of Applied Sciences; Regional Editor Europe of International Journal of Vehicle Noise and Vibration; Editorial Board Member of Chinese Journal of Computational Mechanics; PATTERSON - Editor-in-chief, Journal of Strain Analysis for Engineering Design, (2006-15); POOLE – Editor, 2019 - present Journal of Non-Newtonian Fluid Mechanics (Elsevier);

HALL - Associate Editor of IEEE Electron Device Letters and Editorial Advisory Board of Solid-State Electronics; HUANG - Editor-in-Chief of Wireless Engineering and Technology, and Associate Editor of IEEE Antennas and Wireless Propagation Letter; TU - Editorial Board for Journal of Physics D: Applied Physics, Waste Disposal & Sustainable Energy, Plasmas, and ES Energy & Environment; YI - Editorial Board member of IGRPS Journal of Electronics and Sensors; MARSHALL - section editor (B: Computer and Communications Networks and Systems) for the British Computer Society's Computer Journal, SHEN - Applied Science (Editor Special Issue, 2018 - present).

Membership of Research Councils, national and international committees:
Within the REF period, we contribute to a diverse range of worldwide research councils and committees, as illustrated below.

Some notable examples include: BLACK - Strategic advisory team (SAT) member for EPSRC Manufacturing the future; SAT member for EPSRC equality, diversity and inclusion; D'SA - Member of the EPSRC Physical Sciences Strategic Advisory Team (2019); WILLIAMS - EPSRC Healthcare Technologies Strategic Advisory Teams (SAT); WHITTLE - EPSRC Energy Scientific Advisory Committee (SAC); Member of UKRI Energy Scientific Advisory Committee 2017 – 2021. Our colleagues contribute to peer review of a diverse range research proposals for funding agencies worldwide.



More than 30 of our academics are Full Members and a further 25 are Associate Members of the EPSRC peer review college. We have contributed to the review of funding applications to funding agencies worldwide, as shown above.

UoA12 researchers have been awarded a range of **Fellowships and Prizes** within the period. Selected examples of these include: AKHTAR - Eng/Leverhulme Senior Research Fellowship (2017/18); CHALKER - EPSRC High Value Manufacturing fellowship with Catapult CPI; MERK - RAEng Chair in Emerging Technologies to drive forward an advanced nuclear technology (2020); POOLE - 2015-2020 EPSRC Complex fluids and rheology fellow (established)**;** THEOFILIS - 2015-19: Visiting Professor and Staff Member of the Graduate Program in Mechanical Engineering, Universidade Federal Fluminense, Rio de Janeiro, Brazil**;** TIMME - Industrial Secondment (Competitive Fellowship, Royal Academy of Engineering 2016)**.**

In addition, the UoA has hosted 6 competitive Royal Society Newton Advanced Fellowships awards indicating the attractiveness of our research expertise, infrastructure and facilities.

Some of the **Prizes** awarded include:

- AKHTAR - Bob Bonser Prize for Aortic Surgery (SCTS 2019)**;**
- BLACK - WES Top 50 women in Engineering**;**

- BROWNING - Humboldt Research Award (2019);
- FERRERO, Best Application in Instrumentation and Measurement award by the IEEE Instrumentation and Measurement Society (2016);
- PAOLETTI - EPSRC Rising Star award (2014);
- PATTERSON - Royal Society Wolfson Research Merit Award (2011-2016);
- Sutcliffe and WONG, the IET Innovation Award (2019);
- Sutcliffe - RA Engineering Silver Medal for outstanding contribution to British engineering.
- WILLIAMS – EPSRC Recognising Inspirational Scientists and Engineers (RISE) award (2014)
- YAN, Grand Excellence Prize, China National Forum on SF_6 Alternative Gases (2017).
- ZHAO - Ivor Jenkins Medal, Institute of Materials, Minerals and Mining (2015).

Invited keynotes, plenary lectures or conference chair roles Engineering researchers have contributed to a wide range of dissemination through conferences, workshops, industrial forums and other universities. In total, the number of invitations to speak exceeds 250, in no fewer than 25 countries worldwide.

4.5 Wider contributions to the economy and society

Our Engineering researchers at have contributed to a range of activities influencing the local and national economy, as well as the health of the wider society including policy development, educational outreach, business support and public awareness.

- MARSHALL, was Principal expert witness (June 2019) in a large multi-national trial, held at the Royal Courts of Justice, London, involving Conversant Wireless Licensing S.A.R.L. (USA, Luxembourg) and Huawei and ZTE (China). The case involved patent infringement for 3G, 4G and LTE cellular networks and mobile phones.
- JUMP and PATCHETT are part of an interdisciplinary team involved in research to develop new robotic technologies to improve efficiency and reduce human exposure to extreme and hazardous environments - part of £2M funding awarded through participation in three research hubs funded under the Government's Industrial Strategy Challenge Fund.
- CHALKER is leading on the provision of expertise in glass and refractory materials in a unique industry-backed research and technology consortium, Glass Futures that has been awarded £9M to revolutionise and ultimately eliminate CO_2 from glass production. The new pilot facility, based in St Helens, will be one of the world's first openly accessible, commercially available, multi-disciplinary glass melting sites with provision for research and development trials to decarbonise the UK glass industry.
- The £10M ERDF funded project LCR 4.0 led by VEC has supported > 300 SMEs in Liverpool City Region, creating >80 new jobs and £22.5M of additional GVA. The project was listed as one of the Top 100 European digital champions in the Financial Times (2018) and is referenced as a best practice initiative in the Made Smarter Review (2017).

As the COVID-19 pandemic confronts the world, engineering researchers at Liverpool are applying their leading expertise to address the resulting challenges to our society.

- WALSH is utilising the plasma technology developed at UoL to address an urgent need for rapid ambulance sanitisation, enabling crews to rapidly clean their own ambulance without large quantities of liquid disinfectant or returning to a cleaning centre.
- MASKELL is developing a data fusion system for significantly better decision support for COVID-19, for example, daily forecasts of ICU bed demand for each NHS region in the UK to help decision makers agree appropriate social distancing measures.
- Academic staff and PhD students in the School of Engineering and Architecture, answered the call to produce protective face visors for the COVID-19 pandemic, using the latest in 3D printing and laser cutting technologies. Unilever, who have a strategic partnership with the

University, provided support with scaling up production of the visors and AMB with Smurfit Kappa, a leading provider of packaging materials donated materials to the project.

4.6 Future plans and strategy

Following a sustained period of significant investment in our research spaces and facilities, the next phase of our strategy *"Sustain and Grow"* is to build upon this new capability. The flagship DIF and Sensor City will be exploited to open up new opportunities for our researchers and in particular for the ECRs recruited in the current period. Through the strategy to *"Invest and Develop"* we will continue to build our academic teams of researchers focusing on the research teams described in Section 1. As we emerge from the pandemic, our strategy for *"Civic and Global"* outreach will present new opportunities to work with our local community, whilst continuing to nurture and extend our international research partnerships and collaborations, such as the UK-Jiangsu programme.