Institution: Brunel University London

Unit of Assessment: 12 – Engineering

1. Unit context and structure, research and impact strategy

Context and Structure

All Brunel research activity is organised into multidisciplinary Institutes: 1) Energy Futures, 2) Environment, Health and Societies, 3) Materials and Manufacturing, 4) Digital Futures. Each drawing together researchers from across the university. Engineers are conducting research in all four Institutes, and lead in three: Energy Futures (**Tassou**), Materials and Manufacturing (**Bahai**), and Digital Futures (**Sadka**). In addition, we have four large-scale specialist units: Centre for Sustainable Energy in Food Chains (CSEF), Wolfson Centre for Materials Processing, Brunel Centre for Advanced Solidification Technology (BCAST), and we lead the National Structural Integrity Research Centre (NSIRC).

We encourage researchers to belong to multiple institutes or centres, leveraging interdisciplinary skills and knowledge. All institutes have members from non-engineering disciplines (a central element of our strategy) making us flexible to emerging research challenges and the needs of industry. Our vision since the founding of Brunel University London is to tackle problems fundamental to the UK's prosperity, and to develop important technologies to meet current and future industrial needs. Our approach is to discover and apply fundamental knowledge to innovate for the benefit of society.

In REF2014, we entered the General and Mechanical UoAs. The unified Engineering panel, and our strategy that has radically changed the way we organise and conduct research, means that in this submission we are organised in five themes: 1) Energy and Environment, 2) Applied Mechanics and Structures, 3) Materials and Metallurgy, 4) Sensors and Digital Systems, and 5) Manufacturing and Design. We show how these map to, and have developed from, our previous structure and the value our strategy has delivered.

Research Strategy

The University's high-level research strategy is summarised as:

- Recruit the best possible researchers at all levels (doctoral to professorial).
- Reward successful researchers.
- Provide seed-corn funding to promising new areas to build capacity.
- Reward successful groups with critical mass by investing in facilities and give autonomy to form centres of excellence that are international competitive or leading.

Taken together, these points ensure intellectual sustainability by giving flexibility for researchers to develop new themes, alter the direction of current programmes, combine groups, or change research area entirely. Within Engineering, our strategy creates solutions to internationally important problems and to train doctoral researchers as multidisciplinary thinkers.

The main elements of our REF2014 plans were to:

- Transform the specialised research groups in departments into multidisciplinary themes grouped into research institutes and centres.
- Increase total and per capita income.
- Build facilities for the Brunel-led National Structural Integrity Research Centre, the EPSRC Centre for Sustainable Energy in Food Chains, and a novel purpose-built Advanced Metal Casting Centre.
- Ensure the long-term sustainability of our EPSRC IMRC for Liquid Metal Engineering.
- Develop a Doctoral Training Centre related to the food sector.
- Expand staff and facilities in our Applied Mechanics and Energy themes.
- Invest in an Environment Engineering theme.
- Secure funding for a new computing facility for big data analytics in the engineering sector.

These have been achieved (or exceeded) and detailed elsewhere is this document. Demonstrably, we are operating at a higher level than during REF2014. This is testament to the efforts of individual staff and the impact of a clear, well thought out strategy that staff could get behind and support to the fullest extent. Our main achievements in this period are:

- Won total funding of £133.2M, treble the value in REF2014 (£44.7M).
- The average income per person is £838k (census headcount), or £683k including leavers and retirees.
- Four people awarded FREng in this period.
- Achieved our first UKRI Future Leaders Fellowship.
- Won six RAE Distinguished Visiting Fellows (overseas) and seven Visiting Professorships.
- Won three Rutherford Fellowships.
- Attracted £64M of industrial inward investment.
- One of only five universities (Cambridge, KCL, Manchester, UCL) to win Research England UKRPIF funding for three or more major capital research projects with industry.
- Largest InnovateUK portfolio for our KEF peer group (13th overall).
- Raised £1.2M additional support from companies for 29 Industrial Case awards.
- Created four new industrial strategic partnerships.
- Promoted 11 REF2014 Early Career Researchers (ECRs, two to Professor).
- Won an EPSRC Doctoral Mobility Pilot grant.
- Part of two UKRI Doctoral Training Centres.

Brunel is an EPSRC strategic partner, with engineering forming 80% of the University's research income. In addition to creating a structure of institutes to better enable our intellectual communities to foster research and innovation, a key element of our strategy has been to seed new areas with frequent (modest-sized) cash investments allowing individual staff to develop techniques for new application areas. As part of this investment we support staff to start new collaborations with individuals or groups elsewhere in academia or industry. The success of an investment is measured by the creation of a grant application, a KTP arrangement, or some other output which indicates that further support is warranted.

Our strategy is underpinned by the highest expectations of research integrity and guided by the principles of 'Open Research'. In all groups and teams, decisions and strategies follow the University Code of Practice for Equality, Diversity and Inclusion. Our Open Access mandate is part of our IKE strategy, with all staff expected to place new research publications in the University's research database (BRAD) and the University's research archive (BURA) subject to publishers' copyright permissions. Library Services support individual staff with this process as required. Compliance rates for BRAD and BURA form part of the University Research Plan KPIs. Individual compliance with the OA mandate forms part of an individual's Personal Research Plan and the University's promotion criteria.

Overall, our strategy is vindicated by the trebling of our research income for this UoA since REF2014. We are especially pleased with the success of our REF2014 Early Career Researchers (ECRs); they have won 29 grants totalling £3.1M. This equates to £259k per capita, which is good in the light of our established academics winning approximately double this (£683k per head). Like REF2014, our ECRs are spread across the five areas, though our investment in Environmental Engineering has doubled the number of ECRs in the Energy and Environment theme. The staff entered in this submission have, since the last census date, published more than 3560 papers (Web of Science) with over 51,600 citations (15 per paper). We outline the current activities of our five themes and give highlights to demonstrate the success of our strategy.

Energy and Environment (EE)

This theme's 37 staff, won 135 grants worth £24.2M, and graduated 102 PhD students. There are five groups in this theme with several staff working across groups. The Environmental Engineering and Resource Efficient Future Cities (REFC) groups are newly formed as part of our REF2014 strategy. REFC integrates our transport and urban energy use researchers across the university.

The Advanced Powertrains and Fuels (APF) group is one of the most active experimental and modelling groups in Europe and a long-standing expertise of Brunel. The main strengths are improving the efficiency through developing low temperature combustion processes, novel technologies for manufacturing and combusting bio-fuel, and regenerative braking. The research on regenerative braking has been successfully commercialised. The group is a core member of the European Network of Excellence on Combustion Engines, and the UK Consortium on Turbulent Reacting Flows (UKCTRF).

The Energy Efficient and Sustainable Technologies (EEST) group is particularly successful in attracting industrial support for its fundamental and applied work on energy use in food chains, solar-thermal and PV technologies, advanced heat and mass transfer, environmental control of buildings (heating, cooling, ventilation, and refrigeration), heat to power generation, and single and two-phase heat transfer. **Tassou** heads Brunel's activities in the BBSRC-funded Food Biosystems DTC. This £11.2M multidisciplinary programme examines biological processes across the Agri-Food system.

Our Environmental Engineering (EnvE) group is rooted in flood and coastal engineering, strongly supported by a £3M programme from HR Wallingford and the Environment Agency. The areas where we have established expertise are geotechnics, tsunami effects and coastal resilience, interaction of coastal structures and extreme geo-environmental coastal hazards, probabilistic and deterministic methods for coastal hazard assessment, and tsunami warning systems.

Our Resource Efficient Future Cities (REFC) group incorporates staff from 12 academic departments. The key areas of expertise are energy efficient building retrofits, cost-effective zero emissions buildings, urban climate and micro climate impact on building energy efficiency, sustainable infrastructure construction and maintenance, transport energy use, additive manufacturing for concrete structures, bio-based construction materials, and integrated systems for sustainable development. One example of how this strategy has been effective is **Ceschin** being appointed as an Africa-UK Trilateral Research Chair in Energy Security in Poor Urban Environments funded by National Research Foundation (NRF) of South Africa and the Newton Fund through the British Council.

The well-established Smart Power Networks (SPN) group develop computational tools for analysis, control, operation, management and design of electricity transmission and distribution systems with a high penetration of renewable resources and on the development of power electronics for efficient power conversion. They have maintained their long-standing relationship with National Grid, securing on-going direct financial support.

Applied Mechanics and Structures (AMS)
This theme's 31 staff, won 108 grants worth £20.3M, and graduated 47 PhD students. There are two groups in this theme. The Mechanics and Fluids (M&F) group was restructured (from the Applied Mechanics Group) as per the REF2014 strategy to accommodate the creation of NSIRC. M&F incorporates the Civil Engineering group formed at the end REF2014 (growing to eight staff as planned).

We won the competition for National Structural Integrity Research Centre (NSIRC, with Cambridge, Manchester, and UCL) on the strength of our computational and applied mechanics research. In this period, NSIRC staff (stabilised at 10 people) have completed >50 industry-funded research projects. Much of NSIRC's work is focussed on developing innovative, fit-for-purpose technologies and design rules, and long-term asset management. Our key areas of expertise enabling this are: nonlinear transient finite element methods, impact mechanics, risk-based inspection strategies and critical assessment, non-destructive testing, structural health, condition monitoring, process modelling for metallic additive manufacturing, and constitutive response of materials for strength, damage and shock response.

The Mechanics and Fluids (M&F) group focuses on structures and aerodynamics. The work on steel structures is predominantly modelling of behaviour under extreme conditions such as fire,

impact, seismic loadings, and fluid-structure interactions. Development of new deformation-based design approaches for stainless steel structures is another key activity. This new M&F group has been bolstered by growing our aerodynamics research. The significant level of investment is broadening our expertise to incorporate molecular dynamics and areas such as energy-efficient cooling for battery systems. Aero-acoustics and flight physics remain core areas for our aerospace team.

Materials and Metallurgy (MM)
This theme's 22 staff, won 124 grants worth £68.9M, and graduated 35 PhD students. The two groups in this theme are as REF2014.

The approach of the Brunel Centre for Advanced Solidification Technology (BCAST, formed 2002) to the use and processing of metals epitomises the 'circular economy'. The investments made in previous RAE/REF periods have enabled the BCAST team to grow to 15 academics and 12 RF/SRFs. BCAST operates a globally unique and comprehensive combination of casting, melt conditioning, and characterisation facility for liquid metal processing. A major element of our REF2014 strategy was to expand the large-scale processing facilities by establishing the Advanced Metal Casting Centre. With generous industrial support and additional UKRI funding we have been able to go further to establish a second major facility for processing (the combined AMCPC). Another part of our 2014 strategy was to win renewal of the EPSRC IMRC for Liquid Metal Engineering (LiME). This has been achieved by creating the 'Future LiME Hub' (£10.1M, EPSRC) collaborating with Oxford, Imperial, Manchester, and Leeds. The hub brings together the facilities for solidification research including: state of the art analytical modelling and molecular dynamics simulation; a range of innovative casting processes; technologies for the engineering and assessment of liquid metals; and an extensive suite of tools for microstructural characterisation.

The Wolfson Centre for Materials Characterisation and Processing (MCP) group's main expertise is in electroluminescence materials and polymer processing. The key activities are developing quantum dot technologies and OLEDs for low energy displays, alternating current luminescence and phosphors as LED colour convertors, nanoparticle phosphors and display materials for lighting and displays, and plastic electronics. MCP has world-leading expertise in polymer processing for a wide range of established industrial techniques, including unique mixing and injection moulding techniques that were developed at Brunel. Current and recent application areas include: fire retardant textiles, biodegradable packaging, and the formulation of biofuels. Work on moulding and extrusion processes has generated a significant portfolio of patents and intellectual property rights, which is reflected in a number of commercial licenses and spin-out ventures.

Sensors and Digital Systems (SDS)
This theme's 29 staff, won 45 grants worth £4.9M, and graduated 132 PhD students. The two groups in this theme as REF2014.

The Communications group focus on real-time signal processing, and transport and delivery over heterogeneous wireless, broadcast, and mobile networks. The main application areas are within the media, energy, environmental, security and defence, manufacturing, and medical industries. The core expertise and reputation are in ad-hoc wireless networks, cognitive communications, cross-layer optimisation, interactive broadcast systems, personal mobile grids, service discovery, applications in telemedicine, and wired and wireless integration networks. Our expertise in 5G software and hardware communications technologies are contributing towards the evolving 5G standards. We are developing complementary technologies for effectively interworking with 5G systems e.g. uDevelop a 5G compliant platform for developing and demonstrating intelligent services for the entertainment, health, transport, factory, energy and any other vertical industries.

The Sensors and Instrumentation (S&I) group develops and exploits detectors, electronic systems, and data analysis methods. They apply their work to remote instrumentation and control, high energy particle physics, space applications, and healthcare systems. The sensors team has >25 years of experience in effects of protons, electrons and gamma rays on CCDs using our in-house Cobalt-60 sources. In applying this expertise to the successful use of CCDs in space they have gained a detailed understanding of the space radiation environment and its effects on their

operation. They use computational modelling of the space radiation environment for a number of mission orbits and profiles, supported by experimental testing of CCDs to assess their performance and operation following radiation damage. Example missions include: XMM-Newton, Gaia, GeoSCIA, and ExoMars (European Space Agency), and Chandrayaan-1 (India). The healthcare applications team has expertise in Lab-on-a-Chip for point-of-care-diagnostics, biometrics, measurement systems for pharmaceutical drug aerosol characterisation, and medical electronics and imaging. Other key application areas are implementing intelligent electronic systems for efficient operation and control of industrial processes, and using ultrasonic and electromagnetic acoustic guided wave technology for non-destructive testing (with NSIRC). A topical example of an application is that led by **Balachandran** for a SARS-CoV-2 test, currently under-going trials prior to approval.

Manufacturing and Design (MD)
This theme's 40 staff, won 86 grants worth £14.8M, and graduated 90 PhD students. Three groups form this theme. The Chemical and Bio-processing (CBP) group are newly formed resulting from the creation of the Department of Chemical Engineering (launched in 2018). In the previous REF exercise Design was entered separately, but our strategy was to develop the engineering focus to integrate better with mechanical and manufacturing engineers. This gave rise to a new group, Sustainable Manufacturing.

The Chemical and Bio-processing (CBP) group builds on the long-standing bioprocessing team. The key areas of research are materials and water processing. The bioprocessing team use novel scalable continuous-flow counter-current chromatographic methods for purifying particles and cells, reactions, and filtration. One area of importance for CBP is applying engineering analysis to biomedical engineering. Wastewater treatment, solid waste valorisation, and food process engineering are areas in which CBP have already established an international reputation.

The Design group exploits the principles of human-centred design for integrating design, engineering and sustainability practice. Our main areas of expertise are: material science, biomimetics, product and product-service system design, inclusive design in public transport, assistive technology, design for socio-technical transitions, lifecycle assessment, business modelling, and scaling up co-design and participatory approaches. The key application areas are autonomous vehicles, ageing demographics, digital systems design, and healthcare systems. One example of the impact is design-policy advice to Government for Innovation in UK manufacturing. In the digital realm, our areas of expertise are: strategy models for convergence and cross-mobile IT, web-based technologies to improve knowledge management for collaborative product development and virtual collaboration within globally-dispersed manufacturing organisations, digital health, e-government, immersive technologies (VR, AR and MR), and addressing algorithmic (il)legibility through co-design.

The Sustainable Manufacturing (SM) group delivers economically and environmentally sustainable manufacturing processes based on transdisciplinary design principles linking mechanical and electronic systems, and materials. Our long-standing manufacturing and metrology expertise lies in additive manufacturing and other fabrication techniques, metrology, positioning and manipulation at the micro- and nano-scales using bench-top ultra-precision machines and robotic systems. The target industry sectors are aerospace, built environment, energy, and healthcare. We also specialise in the use of biomimetics to design and develop new materials and structures, design for efficient circuit fabrication using 2D printing technologies, and smart manufacturing processes for low power electronics and embedded systems. Our Quality Engineering and Smart Technology (QUEST) programme is developing the core science and technology for Industry 4.0 by applying advanced sensors, metrology, and quality engineering systems exploiting internet of things, robotics, data science, machine learning and AI. Other expertise lies in supply chain management systems modelling and simulation, agile manufacturing, digital enterprise technologies and energy-efficient methods. The micro-nano manufacturing team focus on integrating high-precision machines, micro-cutting mechanics and physics, molecular manufacturing with application to chemical engineering, the pharmaceutical

industry and 3D-printing fabrication. We have significant expertise in multi-scale multi-physics modelling and analysis providing the foundations for our engineered systems.

Impact Strategy

The Impact and Knowledge Exchange (IKE) for Engineering has five strands with the explicit aim to co-create activities with the beneficiaries (it is our culture) including industry, policy-makers and regulators:

1) To develop strategic alliances with major national and international companies.

Our current strategic industrial partnerships are with: Constellium, ESAB (Elektriska Svetsnings-Aktiebolaget, Sweden), Heathrow, Jaguar Land Rover (JLR), Renishaw, Spirax Sarco, TWI, and Yuchai (China); and CBMM (Brazil). Examples of achievements are:

a) Partnering the Heathrow Research Centre for Airport Technology. This is expanding to incorporate social science and digital systems (including human-computer digital interfaces).

b) Our long-standing partnership with TWI has yielded approximately 90 PhD studentships and we have dozens of staff on site. TWI host the Brunel Innovation Centre, the Brunel Centre for Composites, and the National Structural Integrity Research Centre. This alliance is the basis for two impact case studies in engineering (plus one in maths).

c) The Guangxi Yuchai Machinery Group is the second largest engine manufacturer in China with total assets of ¥41 billion and nearly 20K employees. The Brunel-Yuchai joint research centre was set up in 2010, with the most prominent projects being the world's first air-hybrid engine for buses and the new EURO6 heavy-duty diesel engine.

d) The Constellium partnership has led to multi-million pound research programmes, including establishing an R&D Centre on campus, with impacts on the automotive industry such that this alliance is the basis for an impact case study.

2) To engage UK SMEs with our research base.

Our Co-innovate programme (launched 2012) was funded by the European Regional Development Fund (£8M). The second phase started in 2016 and continues to provide research innovation support to SMEs by accessing academic expertise, equipment, and laboratories. Our programme has assisted >260 companies, with 45 receiving in-depth collaboration, helping these businesses innovate, differentiate and compete successfully in the marketplace.

3) To provide a platform for fledgling SMEs and entrepreneurs through access to our product research and development expertise.

The Impacting Business by Design (IBbD) programme addresses government objectives of improving business productivity and competitiveness by transforming their ability to commercialise design innovation and bring new products to market. IBbD is pioneering a research-informed practitioner-led way of businesses and universities working together to create and sustain relationships and activity beyond an individual project or series of projects.

4) To help established SMEs innovate and grow.

The two elements of this strand target directed assistance to innovations at higher TRLs:

a) Central Research Laboratory: an internationally recognised SME accelerator and the UK's leading programme for product makers and hardware pioneers. Located near our campus, it was funded by HEFCE/EU (£4M) which leveraged an additional £12M from other sources making it the largest hardware prototyping accelerator and incubator in the UK. Following this success, a joint venture with U+I was formed to create a sustainable ecosystem for hardware start-ups.

b) Brunel Innovation Voucher Scheme: started in 2017 to promote collaborative innovation with UK SMEs by offering vouchers for the costs of accessing our facilities and staff. The vouchers (up to £5k) can be used for developing new products, processes, or services that will help the company innovate and grow. The company contributes an equal value in cash or in kind (such as staff time, materials or equipment) or a combination of both.

5) To incentivise academic staff to develop their research outputs into products or services.
If a piece of research, perhaps developed with a doctoral researcher, does not fit established relationships with organisations and companies, we give the practical support and advice to independent development of the idea. The two elements of this strand assist academics in negotiating the commercialisation maze:

a) Entrepreneur in Residence: Dr Alex Reip (Oxford Nanosystems) supports commercialisation and entrepreneurial activities (0.2FTE, £40k, the Royal Society).

b) EPSRC Impact Accelerator Account (IAA): is targeted at three strong existing areas (automotive, energy, structural integrity) and an emerging sector (digital). An example of support was creating the Automotive Hub. A notable Hub-funded project to bring fundamental researcher closer to commercial exploitation was a variable geometry turbine design for advanced turbocharger applications to reduce emissions. The funding supported early market research, IP state-of-art reporting, and early computational performance assessment. Another project benefitting from IAA support (NSIRC) was the correlation of macro-element models to high-fidelity FEA for crash resistance optimisation. Macro-element models run in seconds rather than hours, providing a useful tool for stochastic design exploration.

In terms of how our Impact Case Studies (ICSs) relate to the strategy, we note that four are with large companies, four with SMEs, two from internally generated activity, and three from our strategic partnerships. Our support for academics to build trust with companies, creating long-term relationships, is a strong driver of our impact strategy. Sometimes this leads to a strategic partnership e.g. the BCAST relationship with Constellium. But strong relationships do not have to be large-scale, excellent examples are **Kalganova** (MD) and Caterpillar, **Taverdi** (MM) and Elster, and **M.Fan** (EE) and Ecodek; all yielding ICSs. **Kalganova's** optimisation of agile supply chains improved the capability of handling complexity and big data, whilst **Taverdi** ran a long-term programme developing polymer-based water meters. **M.Fan** won three EU grants which produced the under-pinning science for developing carbon-negative construction products from waste materials. One collaboration giving an ICS was instrumental in developing the relationship between TWI and Brunel; **Balachandran** (SDS) and **T-H.Gan** (MM) worked together on high-temperature transducers for monitoring nuclear reactor vessels.

Research and Impact Strategy: 2020 Onwards
Commensurate with the University Research Strategy, Engineering is moving to an 'Open Innovation' approach to collaborative research. This diminishes barriers to, and enhances opportunities for, research collaboration with industry. Our impact strategy capitalises on the UK Government's Industrial Strategy, through increasing productivity by addressing the skills gap and creating research-led innovation. The University strategy is to make all our themes and groups fully challenge-led and aligned with the four cross-campus institutes:
Energy Futures: innovation for the provision of clean air, food, energy and water through the efficient use of resources, transformative economies and behaviours, the development of smart cities, and climate change impact mitigation.
Environment, Health, and Societies: innovation for technologies for planetary health, environments and (local/global) human health and wellbeing. For communities, we emphasise technologies that assist in sustaining and enhancing the quality of life through economic and social benefits, security, and climate change impact mitigation.
Materials and Manufacturing: innovation for improving the sustainability, design, integrity and performance of manufacturing processes and products, through more efficient use of resources, development of novel materials and pioneering Industry 4.0, leading to socio-economic and environmental benefits.
Digital Futures: cross-cutting innovation for healthcare, education, manufacturing, and the built environment, while mitigating the impacts of climate change and ageing populations, and protecting against cyber-crime.

Our current groups, and teams are well-aligned with the institutes, particularly Digital, Energy, and Manufacturing (where we are leaders). Engineering already contributes to the health theme (e.g. diagnostics) and will contribute to secure connected communities. We are creating mechanisms to include researchers from non-engineering departments, enhancing our multidisciplinarity. We

have learned much from the current arrangement of research groups and we see these new themes as a natural extension of our current direction.

The University will prioritise resources and appointments to complete the integration with these strategic challenge-led areas, balanced with emerging areas of strength. We recognise the opportunities to diversify our portfolio of research income and range of activities for our business-engagement programmes. We will continue developing comprehensive relationships with new partners by exploiting industry-based PhDs, staff mobility, fellowships, collaborative research and commercialisation. We will monitor our research activities against our ethical principles, ensuring the highest levels of research integrity.

The growth and incredible success of BCAST is an example of what our IKE strategy can deliver with appropriate investment. Another example is success is our strategic investment in energy use in the built environment, culminating in winning the UK Centre for Sustainable Energy in Food Chains. We recognise that not every strategic initiative will succeed to the same extend, indeed some will fail. Our approach to investment and risk is an important part of why our engagement with companies of all scales has been successful and why we place much emphasis on enabling academics to pursue commercialisation and to engage in entrepreneurial activity if they so choose. The focus for our next major KE strategic initiative is NSIRC as we recognise the international significance of the work being conducted by our staff in this group.

Future Plans for each Theme

Energy and Environment

APF is shifting its emphasis to improve efficiency of the difficult to decarbonise larger-scale engines. In support of **X.Wang** (UKRI Future Leaders Fellow), £203k is already secured for a picosecond laser for quantitative studies of nonthermal plasma discharges. We anticipate new appointments in the APF and EEST teams. The importance of environmental engineering as a coherent research area is developing for us and we will be making further investments in flood and coastal engineering to strengthen the EnvE team. The group is predominantly ECRs who with nurturing and the right investment have the potential to make significant impact. The REFC and SPN teams will transform into research centres in 2021. We will continue building our investment in the UK Centre for Sustainable Energy in Food Chains; the domestic production of food is of increasing importance.

Applied Mechanics and Structures

Our long-standing strength in computational mechanics will be maintained with investment in high-performance computing. New appointments, expanding our capacity and capability in aerospace, will focus on aircraft structures and aerodynamics. A key target for this group is exploiting the recently won EPSRC-funded Tier 2 supercomputing facility (£4.5M), in particular by linking length-scales from the atomic and molecular to macro-properties to understand novel materials for structural applications. Our CFD expertise will be expanding by collaborating with our new flood and coastal engineering team. We will consolidate the expansion of experimental staff with investment in laboratories; >£700k already secured (see Section 3).

Materials and Metallurgy

The second phase of BCAST's large-scale facility is the casting hall (completion, 2021). The third phase of the combined Advanced Metal Casting and Processing Centre is the addition of a new £16M building (construction, 2021-22) for the processing line. Another project of key importance to execute successfully is the UKRI Interdisciplinary Research Centre for Circular Metal awarded November 2020. Other new directions for BCAST include developing aluminium packaging as an alternative to plastic, and expanding their casting and processing capability for magnesium.

Resulting from the untimely death of Prof P. Kathirgamanathan, work on quantum dot materials for low-energy displays is being merged with that on luminescent materials creating a unified programme. The electron microscopy and materials analysis facilities of the Experimental Techniques Centre is being merged with the processing capability of the Wolfson Centre. The newly appointed joint Director (**Fern**) is leading this ambitious plan to create a powerhouse of end-

to-end materials discovery, analysis, and processing. Various retirements are allowing us to rebuild and reshape the MCP group to encompass the materials challenges for the 21st century spanning the physical and biological sciences, and ways of creating engineering applications. To this end, we have secured investment for equipment (see Section 3).

Sensors and Digital Systems
The S&I group has been consolidated in this REF period, maintaining high levels of multidisciplinary collaboration using electronic systems. SDS members will continue creating impact by applying their expertise to cross-cutting and multidisciplinary problems where innovative sensor solutions are required across the University's four institutes. For example, expanding activity for Industry 4.0 with the MD theme, specifically developing robotic systems. Moreover, we will create new opportunities for digital healthcare, including with the newly formed Brunel Medical School, which is co-ordinating health research across the University. Both the Communications and S&I groups will be taking lead roles in the newly formed Brunel Institute of Digital Futures. The Communications group will continue expanding collaboration with other 5G research centres across the world to establish end-to-end connectivity through 5G Cores for demonstrating enhanced mobile broadband and ultra-reliable low latency services. Our high-performance computing facilities are led by staff in the S&I group, serving not only the GridPP collaboration, but also our computational solid and fluid mechanics groups.

Manufacturing and Design
Ensuring success of the new UKRI-funded Doctoral Training Centre in Food Systems is a priority. Being part of this consortium vindicates our investment over the last decade in the under-pinning research for energy use in the retail sector. Also, in the CBP group, we anticipate additional support for the work of our research carbon capture and use. The appointment of **Dong** as head of the Brunel Design School is injecting new leadership and vision into human-centred design. MD (and S&I) staff will continue driving innovation through The Central Research Laboratory and its expansion over the next five years offers exciting opportunities for collaboration in new industries. We will transform the Impacting Business by Design (IBbD) initiative into an international scheme, initially in China. This new venture will keep the principle of using co-innovation for improving business productivity and competitiveness by transforming the ability to commercialise design innovation and bring new products to market. The Design group are leading (**Garaj** with assistance from **Choi**) the international expansion of the StoryFutures collaboration to China, which we anticipate being an impact case study in the next REF exercise. With the SM group we expect to continue investing in the applications of robotic technology to manufacturing. The precision machining group will build on the physical and electrochemical micro- and nano-machining, continuing to develop new applications for the aerospace and biomedical industries.

2. People

Staffing Strategy and Staff Development
Our policy is that all staff appointments are research-led. Our strategy for the coming REF period is to increase the number of academic staff to 170-180 (from 159). We expect to appoint staff with backgrounds other than purely academic to maintain our vibrancy and to further improve our societal impact. We have learned how to develop staff with significant experience in industry to reach the highest levels of academic performance (teaching and research). This approach has proved successful in the current REF period, and we will capitalise on this for the next. Our recruitment policy is to focus posts in the key areas highlighted in our strategy. This will give us critical mass in the five research themes around which we are organised, but it also identifies emerging areas where the application of engineering could create significant societal impact. All new appointees are integrated into our research culture through membership of the multidisciplinary themes, enabling them to engage with cognate researchers from across the University. In addition, new staff are supported to generate their own research programmes and to seek national and international collaborators. Our strategy rewards research groups demonstrating grant income success with new posts, and provides mentoring at all levels.

Equality and Diversity
In the previous REF period, the University appointed 'Equality Diversity Champions' to provide leadership in creating and maintaining an inclusive culture. The University made this role more prominent in 2016 by creating Associate Deans for Equality and Diversity, attracting an enhanced stipend and agreed workload allocation (20% FTE). Through internal competition, Engineering appointed first **Cole** (SDS) and currently **Kolokotroni** (EE). Engineering holds an Athena SWAN Bronze Award. Key policies include: flexible working for researchers and support staff, home working arrangements, a generous maternity leave policy, and training for interview panel chairs. We offer Athena SWAN Research Awards to support academic and research staff who have had a period of maternity leave, statutory adoption leave or significant additional paternity/adoption leave (four months or longer) as they recommence their research. The funds are competitively awarded on the basis of a submitted research proposal and may be used to purchase equipment, employ research assistants or, where appropriate, teaching buy-out.

Brunel, as a research-intensive university, is submitting 100% of all eligible academic staff. We followed the processes set out in our Code of Practice for the fair and transparent identification of independent researchers and to ensure that the submitted outputs provided a balanced and unbiased representation of the work of our diverse academic community, their characteristics and contractual positions (age, disability, race, sex, part-time workers and fixed-term employees). Output selection was monitored through regular Equality Impact Assessments. Our Equality Impact Assessment indicates that the outputs submitted for Engineering are a well-balanced representation of the protected characteristics and contractual positions of staff. This includes the 19% female staff and the 16% of staff on fixed-term contracts all contributing at the expected level to the outputs. The 38% of staff of Asian ethnicity contribute 32% of the outputs.

We operate a long-standing and vibrant Women in Science and Engineering group spanning the whole university and all grades (including PGRs), and is led by **Gratton**. **Cole** and **Gratton** have secured grants totalling £59k for encouraging girls to take up STEM subjects. We take part in Advance HE`s Aurora leadership development programme. It is run as a unique partnership bringing together leadership experts and higher education institutions to take positive action to address the under-representation of women in leadership positions in the sector; **Cole**, **Gan**, and **Kalganova** have benefitted from this scheme. The Women in Brunel Engineering and Computing (WiBEC) programme supports female graduates and undergraduates to attain their full potential in the engineering or computing industry sectors. The programme consists of a bespoke mentoring scheme (all mentors are professionals), personal professional development training and visits to industry. Now in its 7th year, >600 female students have benefited from this support and a number are returning as mentors.

Research and Knowledge Exchange (KE) Leave
For all subject areas regardless of career stage, Brunel offers schemes to assist staff in developing new research areas and proposals. We routinely offer traditional research leave, but as part of our recognition of the importance of KE between academia and our user communities we have two additional schemes (one inbound, one outbound). These facilitate the two-way transfer and exchange of knowledge, expertise and skills between Brunel and its user communities for mutual benefit. Our KE Secondment Scheme (KESS) is aimed at higher-level external professionals with relevant experience and skills to carry out an agreed programme of KE activities based at Brunel. For Brunel staff the KESS gives academics leave (one term to one academic year) to concentrate on a programme of activity that will lead to specific, identifiable and measurable outcomes of benefit to the University's overall KE aims. In both cases the aim is to strengthen long-term relationships with a view to developing and sustaining future collaborative opportunities.

Academic Lifecycle and Professional Development Review
On appointment, all ECRs are assigned a mentor, have reduced teaching and administrative responsibilities throughout probation, receive priority in the allocation of our DTA research studentships, and are appraised annually by the appropriate Head of Department (HoD) and research theme leader. It is expected that ECRs are promoted to Senior Lecturer upon successful completion of probation. Start-up funding of £15k is offered, upon internal review of a short

proposal, to initiate a project, acquire equipment, and to travel to conferences to create a network of collaborators. The successes demonstrate the efficacy of this scheme. **Cashell** (AMS) and **Pisica** (SDS) were able to find industrial collaborators to fund industrial studentships with TWI and Thames Water, respectively. **Ghaffar** (EE) started his laboratory for sustainable construction materials, contributing to him winning an EPSRC grant and recently funding from the British Council. This gave the University confidence to increase investment in laboratory infrastructure for 3D printing of concrete items with structural integrity. Another example is that of **Singh** who began experimental work on solar concentrators and developed an international collaboration, winning two grants under the UK-India Education and Research Initiative. Such early success bodes well for the future.

All senior lecturers are appraised annually by the appropriate HoD and research theme leader. Readers and professors agree annual targets with their HoD, with annual pay rises linked to performance. Senior academics looking for leadership roles are offered a six-month programme to develop relevant competencies. Eight senior researchers in this UoA have taken part since 2014.

All staff complete regular compliance training on: anti-bribery, data protection and information security, health and safety, equality and diversity, and environmental sustainability. Additional mandatory training for ECRs, research staff, and PGRs is required in Research Ethics, Managing Research Staff, and Influence and Impact for Researchers.

Our staffing strategy is enabling us to sustain a balanced age profile with approximately one third of staff in bands of <37 years old, 38-50 years old, and >50 years old. It is not sufficient to simply recruit excellent academics, we consider it central to our strategy to maintain a vibrant cohort of staff ready for leadership at all different levels. We give training and support for ECRs to gain the skills and confidence to lead individual projects, and ready mid-career staff to lead groups and themes. By encouraging gifted and energetic ECRs and mid-career staff, we naturally maintain a flow of people able and willing to take on the responsibilities crucial to carrying out strategy and creating the environment in which others can flourish. As an example, **Cairns** was an ECR in REF2014, since when he won his EPSRC First Grant, was promoted through to Professor, and took on the role of Deputy HoD of Mechanical and Aerospace Engineering. Similarly, **X.Zhou** was promoted from Senior Lecturer to Professor and became HoD for Civil and Environmental Engineering. Recently, a research associate in the APF group **X.Wang** received the support he needed to win Brunel's first UKRI Future Leaders Fellowship.

Academic Appointments and Major Promotions
Since 2014 we have appointed 64 people (30 ECRs, 34 mid-career or senior), and 11 people have retired. Of these 64 positions, 47 are new, an increase of 18% over REF2014 when we created 40 new posts (17 ECR, 23 senior). The combined success of our research and staffing strategies has enabled us to recruit high-quality ECRs with excellent international experience (detailed by theme below). Likewise, we are very pleased to attract mid-career and senior staff with significant industrial experience. Success in research output and grant income have been such that 57 members of staff (13 female) won promotion since 2014, including seven to Professorships.

We note retirements since the last REF, including: Professors Jack Silver, Ian Boyd, and Jim Song (all MM), and Ian Sutherland (MD). Sadly, we report the deaths of Professor Malcolm Irving (EE), Dr. Jie Chen (EE), Professor Poopathy Kathirgamanathan (MM), and Professor Heinz Wolff.

Energy and Environment
Resulting from the success of the Centre for Sustainable Energy in Food Chains we appointed two new permanent research Fellows to support long-term programmes of work relating to food drying systems. **Usman** (APF) was appointed as an ECR in 2016 to support **H.Zhao**, and in 2020 **X.Wang** (APF) won an UKRI Future Leaders Fellowship. **Lai** (SPN) was appointed as an ECR from Leeds. As environmental engineering, and flood and coastal in particular, is a new area which we started in this REF period, there have been nine new appointments, eight are ECRs. Notable appointees are **Rustell** who joined from AECOM after working in the off-shore industries,

Esmaeeli (Minho, Portugal), **Martin-Moreta** (Universitat Politècnica de Catalunya), **Papathanasiou** (Trento, Italy), **Yin** (Cambridge and AECOM), and **T.Zhao** (Oxford, Sichuan). **Ganippa** (APF) and **Jouhara** (EEST) were promoted twice, through to Professor. **H.Zhao** (APF) has been appointed as Acting Vice Provost and Dean of Engineering, and **Tassou** as Director of the Institute of Energy Futures. In total, this theme has made 16 appointments in this period (14 ECRs).

Applied Mechanics and Structures
Nine people have been promoted in this theme. Notably in the M&F group, **X.Zhou** was promoted to Professor, with **Chong** promoted twice, to Reader. **Bahai** was appointed as HoD for Mechanical and Aerospace Engineering, then as Director of the Institute of Materials and Manufacturing. As part of investing to build aerospace two ECRs have been appointed: **E.Smith** (from Imperial) and **Tyacke** (Cambridge). Other new appointments in aerospace are **Adetoro** and **Cardoso** at Senior Lecturer level, with **Deseri** (Trento) and **Lingwood** (QMUL) to new professorial positions. In starting up NSIRC **Vignjevic** was appointed from Cranfield bringing with him five members of the Impact and Structural Mechanics Group. **Gintalas** was previously a Senior Engineer at TWI, and **Mares** was promoted to Reader. **Cashell** received two Athena SWAN awards. In total, this theme has made 16 appointments in this period (3 ECRs).

Materials and Metallurgy
In the MCP group, **Fern** is now the Director of the Wolfson and Experimental Techniques Centres, and promoted to Reader. **Dai** joined us from Newcastle, having previously worked at McMaster and Toronto (Canada), then Adelaide (Australia). **Kazilas** was appointed jointly with TWI in 2016 to lead work on composite materials. **Lahiri** was appointed as an ECR with excellent international experience: Alabama (USA), Tohoku (Japan), and TU Clausthal (Germany). Three members of BCAST have received multiple promotions: **Ji** and **Nadendla** from Lecturer to Professor, and **McKay** from Lecturer to Reader. Six others received promotions. Based on the group's outstanding success **Assadi** (Tarbiat Modares) and **Chang** (Birmingham) have been appointed to new professorial positions. **Subroto** has been appointed as an ECR with excellent international experience: Delft (Netherlands) and Helmholtz-Hamburg (Germany). In total, this theme has made 10 appointments in this period (4 ECRs).

Sensors and Digital Systems
Sadka has been appointed as Director of our new Institute of Digital Futures. Ten people have received promotion in this theme with **Meng** moving from Lecturer to Reader. The memberships of the two groups in this theme have been stable, but **Z .Huang**, has been appointed as an ECR, and **Huda** and **Wu** as Senior Lecturers. In total, this theme has made four appointments in this period with three as ECRs.

Manufacturing and Design
Atherton and **Khir** received Professorships in Engineering Design and Biomedical Engineering, respectively. Our reputation as being applications oriented allowed us to appoint **Kalbassi** from Air Products as Industrial Professor and Director of Research in Chemical Engineering. Another key appointment was **Simons** (from UCL) as Professor of Chemical Engineering and Dean. **Kalganova** and **Katsou** have both been twice promoted (to Reader). **Katsou** is a case-in-point of our approach to investing in staff. Having received internal funding to collaborate with our strategic academic partner (Tampere U, Finland) she leveraged that to lead and win two EU grants. Katsou also received an Athena SWAN award in 2019. We have been able to appoint ECRs with excellent backgrounds: **Hu** (NU Singapore and Cambridge) and **Soltani** (Nottingham and Imperial). In the Design group we have appointed two ECRs **Manohar** and **Souza Dias**, and **Dong** from Loughborough as Head of the Brunel Design School. In the SM group **Mynors** (Sussex) has been appointed as professor and Head of Mechanical and Aerospace Engineering. **Noh** was appointed as an ECR from Kings, but he has international experience gained at Yonsei University (Korea) and Waseda University (Tokyo, Japan). **Schmidt** won a Global Challenges Fellowship and started in 2019, though she will pursue her own programme of work. **Atherton** and **Anguilano** received KE leave.

We have seen a number of staff leave to take-up prestigious appointments elsewhere in both academia and industry: Sharon Baurley (Professor of Design & Materials and Chair of the Burberry Material Futures Research Group at Royal College of Art), Ian De Vere (Associate Dean, RMIT Melbourne), Pieter Desnerck (Cambridge), Peter Hobson (HoD Physics, QMUL), Alain Jacot (Head of Materials Manufacturing and Modelling, ESI Group, France), Ray Kirby (Director, Acoustics Centre, UT Sydney), Koen Matthys (McLaren Racing F1), Barry Rawn (Carnegie Mellon), Savvas Triantafyllou (National TU Athens), and Asif Usmani (HoD Building Services Engineering, Hong Kong PU).

Research Staff: Recruitment and Career Development
Brunel was reaccredited in 2020 for the EC 'HR Excellence in Research' award', recognising our practices for researcher professional development in line with the national Concordat. We implement all aspects of the Concordat through University codes of practice. All appointments are openly advertised. Training is compulsory for interview panel chairs. All research staff undergo a formal induction, probation process, and PDR. Researchers with aspiration to become academics are given opportunities to gain teaching experience. Researchers nearing the end of fixed-term contracts receive help in securing opportunities internally and externally.

Those winning prestigious fellowships are offered open-ended contacts. One example of how nurturing staff yields long-term gains is **Mousavi** (MD) who started as a PDRA, was given support to become an independent researcher, made a permanent member of staff, promoted to Reader, winning a total of £2.0M in the current period.

Brunel upholds the principles articulated in The Concordat to Support the Career Development of Researchers, namely enacting best practice for providing environment and culture, employment, and professional and career development for our research staff. We were reviewed in December 2019 for our HR Excellence in Research Award by a team comprising two UK and one international peer reviewers. They assessment was that "*Overall, we were very impressed with Brunel's activities to support the career development of researchers and their actions relating to this award*", and that "*We consider some of the activities at Brunel to be sector leading, in particular the process they used to co-create promotion criteria and would recommend they are encouraged to write this up as a case study"*. We anticipate continuing innovation to improve the programmes we deliver to our research staff.

PGR: Training and Support
Since 2014, 406 PGRs have graduated in this UoA. Our strategy for PGR is to:
- attract and select students with the greatest potential for high quality research,
- to create cohorts of students with a strong sense of identity to last through their careers,
- create bilateral agreements with companies and research organisations to support PGR,
- train students to be flexible in the application of their new knowledge,
- develop the transferable skills of all PGRs,
- enable all PGRs to gain international exposure,
- enable PGRs to engage with an appropriate business or industrial sector,
- give PGRs confidence in their abilities and achievements.

To support this strategy we have diversified the number and type of funding sources for scholarships. Furthermore, the University has made substantial financial commitments directly in partnerships. For example:
- EPSRC Doctoral Mobility Pilot grant (£857k), supporting social and career mobility by reducing barriers to entry to doctoral training from different groups. Our programme supports nine industry-based PGRs over five years at industrial partners including Constellium and TWI to drive research and innovation in sustainable technologies. We are one of only four universities to receive these.
- For UK Nationals we secured 10 scholarships per year from the Thomas Gerald Gray Charitable Trust (topped-up by the University).
- Secured 29 scholarships with industrial support e.g. TWI, funds five scholarships per year.
- Overseas PGRs have received full scholarships from their Governments e.g. FAPESP Brazil, Colombia, and Kuwait.

- The NSIRC collaboration has graduated 56 PGRs to date.

We are part of two UKRI Doctoral Training Centres:
Sustainable Food Future (UKRI, £5M) with Greenwich (lead), Aberystwyth, City, National Institute of Agricultural Botany, Royal Veterinary College, Sussex, and UCL (**Stojceska**, MD).
Food Biosystems (BBSRC, £11.2M) with Reading (lead), Aberystwyth, Cranfield, QUB, and Surrey (**Tassou**, EE).

And three international partnerships:
Jiangsu Industrial Technology Research Institute: precision manufacturing is the focus. The current four students per year is growing to the stable population of 12 per year FT at Brunel in a 2+2 arrangement.
Chongqing University of Posts and Telecommunications: co-funding scholarships based at Brunel. The focus is electrical and electronic engineering.
North China University of Technology: emphasising the applications of AI.

Brunel has developed a tool called 3D (Do, Disseminate, Develop) to guide each PGR from registration to thesis completion. PGRs are expected to take responsibility for shaping, managing and directing their research training (taking advice from their supervisor) and to reflect on their training and development needs to assist in their future employability. The programme provides tailored skills for research methods, writing, managing, and dissemination. Brunel collaborates with other universities in London (particularly UCL and KCL) in to provide a broader context for PGR development, and opportunities for inter-disciplinary learning, collaboration and networking across institutions.

All PGRs must take part our annual internal PGR Conference. It gives PGRs a chance to speak, present posters, and allows supervisors to see how their PGRs defend their work before they go to an external conference. For progression to year 2 each PGR gives a talk, presents a poster and is interviewed. Travel funds are available to ensure that all PGRs present their main findings at an appropriate conference. Brunel also holds a '3-minute thesis' competition.

3. Income, infrastructure and facilities

Income
In this period, we have won 498 grants valued at £133.2M, a trebling compared with REF2014, with (by value) 42% from UKRI, 26% Government, 11% industry, 19% EU, 1% charities, and 1% other. This gives an average of £838k per head (159 people entered). If accounting for retirees and leavers the per capita income is £683k. Our ECRs in REF2014 went on to win 29 grants with a total value of £3.1M. The new staff appointed have been very productive and raised a total of £4.6M with 35 grants. We have raised £1.2M from companies to support Industrial Case awards.

Our Research Support and Development Office (RSDO) comprises 24 staff dedicated to pre- and post-award operations for grants, contracts, IP, and business development. RSDO co-ordinates activities for supporting interdisciplinary working within Brunel and schemes enhancing success in applying to all funding sources. For example, in preparing major GCRF bids, we offer internal grants (<£20k) to strengthen existing or past strategically significant internationally collaborative research activities with universities and research organisations in developing countries. Our Research Development Fund (RDF) supports initiatives for research proposal development and pump-priming funding of adventurous or interdisciplinary ideas. The RDF also supports activities leading to the generation of external grants such as: the preparation of large-scale proposals, international consortium building for proposals co-ordinated by Brunel, and the buy-in of specialist proposal-writing support.

Major grants where we are the lead or co-ordinator:
- RCUK Centre Sustainable Energy in Food Chains, £12M (EPSRC, £5.7M; industry, £4.5M; universities, £1.8M), **Tassou** (EE).

- National Structural Integrity Research Centre, £82M (HEFCE, £15M; industry, £45M; Regional Growth Fund, £22M), **Wrobel** (AMS).
- Multiphysics and multiscale modelling for safe and feasible CO_2 capture and storage, £2.1M (EPSRC), **Bahai** (AMS).
- Advanced Metals Casting and Processing Centre, £48.2M (HEFCE, £22M; Brunel, £15.8M, EPSRC, £3.9M; industry, £6.5M), **Z.Fan** (MM).
- STEP-Aluminium, £4.5M (EPSRC, £ 2.3M; Constellium, £2.2M), **Z.Fan** (MM).
- Future LiME Hub, £10.1M (EPSRC), **Z.Fan** (MM).
- CircularMetal, £4.4M (UKRI), **Z.Fan** (MM).
- Flexolighting, £4.4M (EU), **Kathirgamanathan** (MM).
- IoRL, £6.3M (EU), **Cosmas** (SDS).
- QUEST programme, £2.3M (Sichuan Mingxin Investment Company), **Q.Yang** (MD).

Energy and Environment
Total raised: £24.2M. Grants: 135. By group: APF (£8.1M, 40 grants), EEST (£9.8M, 54 grants), EnvE (£425k, 10 grants) REFC (£3.9M, 16 grants), and SPN (£1.9M, 15 grants). The EnvE group is new with almost all staff being ECRs.

Darwish exploited the upgrade (REF2014) to the power systems laboratory to develop and test prototype capacitively-coupled cables for transmission and distribution of electrical power. This research, supported by InnovateUK (£1.1M) in collaboration with Enertechnos and TWI, is one of our ICS. SPN has maintained their long-standing relationship with National Grid, securing £626k of financial support in this period. Another ICS resulted from a modest £247k EU-FP7-R&D grant (**M.Fan**) collaborating with Ecodek and other partners on rubber-wood-plastic composites. Within five years, this research led to commercially available products. Other major grants won include **H.Zhao** for ultra efficient engines and fuels (EPSRC, £757k) and **Kolokotroni** for a platform for residential retrofit assessment and demonstrations for near-zero energy and CO_2 emissions with optimum cost, health, comfort and environmental quality (EU, £747k). **Axon** won £260k from InnovateUK to conduct stochastic modelling for the demonstrator for the UK's first solar EV charging forecourt. Launched in 2020, it is led by Gridserve with a total value of £7.5M. **Jouhara** won nine industry contracts and seven InnovateUK grants totalling £1.3M for his work on heat pipes (total of £3.2M, in this period). In part this was enabled by a modest £100k laboratory refurbishment to upgrade the facility to be of industry-leading standard, leveraging investment of £282k from Air Products and Chemicals. **Xia** (EE) led the UKRI Consortium on Turbulent Reacting Flows (17 partners including Cambridge, Durham, Edinburgh, Imperial, Manchester, Newcastle, UCL, Warwick).

Brunel leads the Centre for Sustainable Energy Use in Food Chains (an RCUK End-Use Energy Demand Centre) collaborating with Birmingham and Manchester. Examples of the 24 industrial partners are Tesco, Heinz, Iceland Foods, Kellogg, and Buro Happold. The centre was launched at the end of the last period with almost all of the spend in the current period. Brunel invested £5.5M into the laboratory facilities resulting in 20 grants worth £2.9M.The centre team is drawn from three research themes (EE, MM, MD).

Applied Mechanics and Structures
Total raised: £20.3M. Grants 108. By group: M&F (£3.6M, 23 grants), NSIRC (£16.8M, 85 grants). AMS theme staff won 11 Industrial Case awards with additional cash support from companies of £460k.

Upgrading the anechoic chamber in REF2014 enabled **Chong** to build on his EPSRC First Grant success to win two further grants: £255k (EPSRC) and £50k (Vestas Wind Systems). **Bahai** has won two notable grants in this period, one for multiphysics and multiscale modelling for safe and feasible CO2 capture and storage (EPSRC £2.1M, Brunel £1.2M) and the other for vortex induced vibration and structural integrity of deep-water flexible risers (EPSRC, £583k). **E.Smith** leads our participation in the EPSRC Materials and Molecular Modelling Hub Tier 2 national supercomputing centre (£4.5M) alongside UCL (lead), Imperial, KCL, Lincoln, QMUL, QUB, Reading, and Southampton.

We won the competition for NSIRC at the end of REF2014, thus most of the spend and investment occurred in this period. NSIRC which has attracted £26.3M of inward investment and forms one of our impact case studies. Our collaborators are Cambridge, Manchester, and UCL) with a total project value of £82M comprising £15M (HEFCE), £45M (industrial partners), and £22M (Regional Growth Fund). The partners are BP, Lloyds Register, Network Rail, and TWI. NSIRC has accelerated the translation of science into commercially relevant products and services.

Materials and Metallurgy
Total raised: £68.9M. Grants: 124. By group: BCAST (£61.5M, 72 grants), MCP (£7.4M, 52 grants). AMS staff won 15 Industrial Case awards with additional cash support from companies of £621k.

The success of BCAST (formed in 2002) is testament to what can be achieved with a long-term strategy and significant investment; HEFCE and Research England have contributed £31M and EPSRC £3.9M through the Large Equipment Account. Technical breakthroughs and major industrial backing has been achieved in this REF period, and it forms the basis for an ICS. Collaboration with Constellium started with a single PhD student, but grew to become a University Technology Centre (and EPSRC Prosperity Partnership) with the company directly funding researchers and facilities. Currently, the STEP-Aluminium project is funded with £2.2M from Constellium and £2.3M from EPSRC. Constellium are also leading an InnovateUK project on aluminium for ultra low emission vehicles (total project value £3.0M, Brunel £781k). In terms of other research grants and collaborations the IMRC for Liquid Metal Engineering (EPSRC, £6.9M) was renewed in 2015 to become the Future LiME Hub (EPSRC, £10.1M) with Imperial, Leeds, Manchester, and Oxford. In 2020, UKRI awarded BCAST £4.4M for one of only five interdisciplinary centres for the circular economy. This centre 'CircularMetal' is led by Brunel in collaboration with UCL and Warwick. BCAST is part of another large InnovateUK project led by Nissan for the Alliance Casting European Development Centre (total £9.1M, Brunel £752k). **Fan** and **Scamans** (with **Vignjevic** and **Hughes**, NSIRC) are partners in a project led by Impression Technologies funded by the Advanced Propulsion Centre (total £8.9M, Brunel £860k) to develop cost-effective light-weighting of high-volume vehicle platforms.

MCP remains a strong centre for materials research. A major highlight is **Kathirgamanathan's** research on OLEDs garnering a string of grants including 'Flexolighting', an industrially oriented EU project co-ordinated by Brunel (total £4.4M, Brunel £1.6M) with eight partners. A key project for MCP involves Sharp Laboratories (Europe) in developing materials and deposition process for manufacturing Cadmium-free quantum dot LEDs (InnovateUK, total £1.2M, Brunel £440k). Our work on solar cells has strengthened is this period too with EPSRC-funded projects for advancing the efficiency and production potential of excitonic cells (£1.3M, Brunel £451k). We are partners in the RCUK Strategic University Network to Revolutionise Indian Solar Energy (SUNRISE) with Swansea (lead) and Cambridge, Imperial, Oxford in the UK, Monash and Queensland (Australia), and IIT-Bombay and IIT-Delhi (India). The total project value is £6.6M, with £675k for Brunel. In 2016 we reorganised our activities relating to polymers and composites, resulting in **Kazilas** being our lead on the UKRI's Future Composites Manufacturing Research Hub (£10.3M). The 15 partner Hub, co-led by Nottingham and Bristol, includes Bath, Cambridge, Edinburgh, Glasgow, Imperial, Manchester, Sheffield, Southampton, and Warwick. **Kazilas** is also the academic lead in a project to develop graphene sensors for defect detection and predictive maintenance in composite materials along with Cambridge Nanomaterials Technology and TWI (InnovateUK, total £1.4M, Brunel £226k). Our work with polymer processing is led by **Taverdi** whose work forms an ICS which built on long-term support from Elster.

Sensors and Digital Systems
Total raised: £5.0M. Grants: 45. By group: Comms (£1.2M, 8 grants) and S&I (£3.8M, 37 grants). SDS staff won five innovation vouchers for applications such as biocompatible polymers and colour changing sensor technologies for use within a multi-component smart bandage for wound healing.

Cosmas is co-ordinating a major EU-funded project (£6.3M, Brunel £576k) with 21 partners including Fraunhofer Erlangen (Germany) and Tsinghua (China). The IoRL consortium develops 5G solutions for intelligent buildings. Areas reliant on high-performance computing have been underpinned with £829k of external funding, with **Khan** leading the activities. **Li** secured £458k from Shandong East Engineering Tools Ltd for video data-driven AI for smart manufacturing. This theme provides one of the ICS; **Balachandran** (S&I) in collaboration with **T-H.Gan** and **Wrobel** (NSIRC) have been collaborating with TWI amongst other industrial partners developing technologies for non-destructive testing of major infrastructure. This developed from an EU grant for a long-range ultrasonic system with high temperature capability. An example of the wide range of applications areas, **D.Smith** won funding from the International Atomic Energy Agency for improved scintillator design for thermal neutron detection.

Manufacturing and Design
Total raised: £14.8M. Grants: 86. By group: CBP (£4.3M, 24 grants) Design (£3.1M, 28 grants), and SM (£7.4M, 34 grants). MD staff won eight innovation vouchers for applications such as early stage development of big data analytics tools and implementation methodology for SMEs.

Early success of the newly formed CBP group is seen in the eight grants won by **Katsou**, the key one being an EU project (£10.1M, Brunel £719k) for demonstration of water loops with regenerative business models. **Stojceska** is part of the £5M UKRI CDT 'Partnership for a Sustainable Food Future'. In the Design group **Spinelli** was funded to evaluate the wellbeing and quality of life for airport staff and local residents as part of our strategic partnership with Heathrow. **Atherton** won a series of grants for robotic and autonomous servicing of trains from InnovateUK, train operating companies, and the Rail Safety and Standards Board. We are one of the three-only universities in the industry-oriented consortium for using AI in media production. This consortium (£5.9M, Brunel £528k, lead, **Garaj**) is an UKRI Industry Cluster programme National Centre led by RHUL. We are leading the consortium's international expansion to China. The key Design group grant (£1.1M) is that for the Automotive Habitat Laboratory given by JLR (a strategic partner) to **Giacomin**, we anticipate this forming an ICS in the next exercise.

Bridging the Design and SM groups, **Cavallaro** is our lead on the £4.9M EU MovAiD consortium developing technologies assisting manufacturing of intelligent, passive, and highly personalised kineto-dynamic equipment to compensate human movements (Brunel, £637k). The major grant for the SM group is the QUEST programme with **Q.Yang** winning £2.3M from the Sichuan Mingxin Investment Company to enhance our research on robotics, data science, machine learning and AI for manufacturing. Another key SM success is the collaboration of **Kalganova** and **Mousavi**. In this and the previous REF period, **Kalganova's** string of grants and support from Caterpillar lead to an ICS, whilst **Mousavi** won £2.0M in the current period. Together, they recently secured £317k from The US Air Force Office of Scientific Research to create novel solutions for ascertaining the minimum required information to control and minimise uncertainty during data registration and data fusion.

Buildings and Infrastructure
Since 2014, our strategy has produced investment of £58.9M in infrastructure and facilities across our themes. We added 7,000m^2 of research space, bringing our total to 20,700m^2 (plus 4,000m^2 for offices and teaching). The University's strategic decision creating a 4,500m^2 facility housing several groups provides state-of-the-art space for PGRs, frees-up space for a 10-year refurbishment programme continuing into the next REF period.

The principal recipient of infrastructure spending is BCAST (£37.8M), adding a new 1500m^2 created the Advanced Metal Casting and Processing Centre (AMCPC), forming one the largest and most prestigious facilities for metals processing research in the world. The unique AMCPC scale-up facility is now 3000m^2 in total with £48.2M secured: £22M (HEFCE), £15.8M (Brunel), £3.9M (EPSRC), and £6.5M from industrial partners including JLR, Constellium, Ricardo, Lotus Engineering, Brunel and HEFCE provided one new building each. HEFCE provided £7.5M for new equipment.

For the National Structural Integrity Research Centre, the purpose-built (£15M) 4,500m^2 facility at the TWI site outside Cambridge is creating an internationally-leading industry-facing facility. Our RCUK Centre for Sustainable Energy in Food Chains investment includes a new 1000m^2 building (£2.6M this period, £5.50M total) freeing-up 700m^2 for aerospace engineering (a strategically important area for us). Our Civil and Chemical Engineering laboratories received upgrades of £1.9M, and £0.9M, respectively. Our workshops and research laboratories are supported by 47 technical staff.

Specialist facilities

We maintain and have enhanced a set of world-class specialised facilities, without which our research would not be possible. The stand-out examples are:

Energy and Environment

Our Advanced Powertrains and Fuels laboratory, one of the largest university facilities in Europe, is equipped with 12 engine testbeds and facilities for gaseous and PM analysis, optical diagnostics, engine simulation, and combustion CFD. An expansion in 2018, supported by an EPSRC equipment grant (£800k) in a fully refurbished laboratory (£140k), is equipped with the state-of-the-art high speed laser diagnostic equipment for in-cylinder flow and combustion studies and a full optical engine. It has been used to carry out a joint research project with ChangAn UK and Ford to develop their latest high efficiency gasoline engines, as well as fundamental studies of novel future fuels.

We have invested £1.9M into facilities for sustainable construction. The nano-cellulose laboratory gives new capability in natural fibre composite construction materials, particularly: fibre disintegration; nano-particle production, suspension and drying; and nano-particle tracking analysis. The pavement engineering laboratory comprises non-destructive evaluation, thermography, 3D imaging and sensor technology, and mechanical characterisation for road and pavement materials processing, manufacture, and deployment. Our additive manufacturing facility for construction allows us to print customised and complex 3D designs in a one-step process. A robotic gantry system with various mechanical adaptations allows us to develop innovative printing techniques and strategies for conventional and novel feedstocks to realise complex architectural designs with the required structural capacity. The facility has wet laboratories for developing printable cementitious- and polymer-based materials.

We have a long history of research in thermal engineering with extensive state-of-the-art facilities maintaining our position as an internationally leading centre for heat transfer research. Our facilities include: a 100kW gas turbine combined heat and power and trigeneration facility, a unique CO_2 refrigeration laboratory for system, component, and controls research, and two 80m^3 environmental chambers providing controlled conditions of air temperature, humidity and flow rate for research and development work under ISO23953 conditions. Facilities for single phase and boiling and condensation research in microchannels were key to winning several grants. The hydrogen fuel cell laboratory houses a SOFC test bench for electrical characterisation and interactions with storage devices. An example where significant impact can be made with a modest, but strategically aligned investment, is that of our heat-pipe laboratory (refurbishment and upgrade, £100k). This investment leveraged £282k from Air Products and Chemicals creating a unique state-of-the-art fabrication and testing facility for cryogenic cooling applications. The laboratory has new rigs for heat-pipe based water desalination and filtration work, adding to existing chemical testing and analysis. Other key capabilities in this lab are thermal management systems for high power/energy batteries for heavy-duty automotive battery pack design.

A major success for our long-term strategy of investing in heat transfer facilities and experts was winning the RCUK Centre for Sustainable Energy in Food Chains. The new 1000m^2 laboratory facilities includes a purpose-built large-scale environmental test chamber and other environment chambers for research on full-scale commercial refrigeration systems. Capabilities include energy recovery, process heating, cooling, and polygeneration. Resulting from this investment, the Brunel team has won 20 grants (worth £2.9M).

Applied Mechanics and Structures
The heavy structures laboratories have capacity to examine the dynamic behaviour of steel members, joints and frames (at 250t). We operate various mechanical testing machines servo-controlled actuators and load cells for multi-point bending (at 15t). The dynamics and vibrations laboratory took delivery of a new air-cooled shaker (£250k). Our burgeoning aerospace laboratories operate a 70m^3 anechoic chamber, a supersonic (Mach 2.0) wind tunnel (10cm^2 square cross-section), a unique reconfigurable open-circuit 40ms^{-1} wind tunnel (2500cm^2 square cross-section), a 6-axis flight simulator for studying pilot behaviour under stress conditions, and a fully instrumented 3-translation and 2-rotation scale helicopter rotor.

The National Structural Integrity Research Centre (NSIRC) is a new purpose-built 4,500m^2 facility supporting internationally important work on asset management accelerates the translation of science into commercially relevant products and services. The laboratories are well-founded for testing all major material classes with the broadest range of mechanical and chemical investigations. Capabilities include: metallic and polymeric materials analysis and characterisation, high pressure testing for pipes and vessels, testing in aggressive environments, and re-configurable large-scale facilities for specialised component / structure testing. For example, NSIRC has a fatigue testing machine for full-scale pipes for the offshore industries under aggressive chemical conditions and temperature ranges upto bending moments +/-250kNm and axial preload of 200kN.

Materials and Metallurgy
Our MCP group (the Wolfson Centre for Materials Processing) incorporates extensive facilities for electron microscopy and materials characterisation, catering for research requirements across the physical and biological sciences. The MCP laboratory was refurbished in 2019 (£911k). The Wolfson Centre is the only UK university research laboratories to achieve BS EN ISO 9001:2008, and UKAS Quality Management 015 standard for asbestos analysis (including equipment calibration test certification).
Electron microscopy. A Joel 2100 FEG-STEM for sub-nanometre imaging equipped with a Gatan Vulcan system for cathodoluminescence (unique in the UK with only a small number globally), tomography for 3D imaging, and electron energy loss and energy dispersive X-ray spectrometers. Our SEMs include FIB-SEM, FE-SEM and standard tungsten thermo-ionic emission instruments. The Zeiss Supra and Crossbeam are ultra-high performance FE-SEMs with high-vacuum and variable operating pressure capability and are equipped with energy-dispersive x-ray analysis and electron back-scattered diffraction. The Zeiss is also equipped with a cold stage for examining moist materials.
Spectroscopy. An array of instruments for quantifying elemental composition and analysing bonding structures, including: Fourier Transform Infrared, micro-Raman, time-of-flight secondary ion mass spectrometry, UV-Vis, single crystal, powder and capillary x-ray diffractometers, and x-ray fluorescence. Our FTIR capability is part of our UKAS accredited services, and the qualitative analysis is carried out by functional group identification, or comparison of IR absorption spectra of unknown materials with those of known reference materials, or both.
Surface engineering. Includes complementary techniques such as topography, tribology, and wettability. We have atomic force microscopy capability for analysing micro/nano-scale surface features, from surface roughness to micro-friction and electrical properties. We operate a bespoke plasma-enhanced chemical vapour deposition system designed for depositing silicated and hydrogenated diamond-like carbon coatings for tribological, electrical and optical applications. For RF/DC sputtering and e-beam deposition, we operate SVS V6000 and Mantis Qbox UHV systems.
OLED manufacturing facility. Comprises a Class-100,000 cleanroom housing pilot-scale manufacture and coatings systems for inorganic/metals and powder handling for thin-film deposition and printed coatings. The facility is well-equipped for wide spectral range measurements including Raman and a large integrating-sphere for luminous efficacy measurements of emissive devices.
Polymer processing. Our purpose-built facility is equipped for thermal, rheological, chemical and structural analysis including micro/nano-characterisation, and mechanical and related physical testing. Industrial processing techniques for polymer mixing, extrusion and moulding technologies, including unique mixing and injection moulding techniques developed at Brunel.

The major facility for BCAST is the Advanced Metal Casting and Processing Centre. The facilities contributed to the grain refining process which forms one of our ICS. BCAST has state-of-art characterisation capability, due to be upgraded in the next period with additional investment. The existing facilities and the major investments in this period, give unique capability:
Melting: electrical resistance and induction furnaces (125kW) a 1600t vacuum assisted HPDC, a 600kg aluminium dosing furnace, and a 500kg magnesium dosing furnace,
Casting: a commercial 450t (clamping force) high pressure die-casting machine, a lab-scale direct-chill casting machine (for light alloy billets and two twin roll casting machines thin strip, a 24t LPDC machine for casting thick sectioned components up to the size of an engine block, a twin roll caster with integrated melt conditioning device, a gravity die-casting system, a sand casting line, and direct-chill casting of billets. For processing: a 350t extrusion press, a 1600t extrusion line for full-scale trials, a 3D freeform bending machine, cold metal transfer welding, an electro-magnetic pulse forming-welding machine, micro/macro-CT scanning, a GOM metrology system, and real-time X-ray inspection.
Processing: two *unique* rheoextrusion machines, one each for aluminium and magnesium profiles directly from the melt; and a 550t extrusion press.

Sensors and Digital Systems
The communications networks and signal processing laboratories include configurable booth-type cells, a high-frequency structural simulator, wireless LAN testbeds, a DVB-T/H Delay Diversity TV transmission network, optical spectrum analysers, optical sources and detectors, and 100km of fibre and D-Fibre. The sensors laboratories include a high-rate Cobalt-60 gamma-ray irradiation facility for radiation tolerant electronic and sensor components for applications in particle physics, space science, and medical dosimetry; a 4T superconducting magnet for long-term testing of photodetectors; micro-focus 40kV X-ray source for space science applications; two Class-10000 cleanrooms for developing and evaluating fast scintillators (including fibres).and fluorescent quantum dots. The well-founded electronic systems laboratories include the capability of printing electronic structures on various materials.

Our high-performance computing facility is a Worldwide LHC Grid Tier 2 site and part of the European Grid Infrastructure comprising 4,500 cores (giving 40,000–45,000 HEPSPEC06 of compute power) and 2 PB of on-line storage. Internal connectivity operates at 120 Gb/s, with 4 external connections at 10Gb/s. An additional £829k has been invested in this facility since 2014.

Manufacturing and Design
Our manufacturing and metrology laboratories include a 5-axis UltraMill with 0.1µm accuracy and a 3-axis micro-electrochemical machine, both make complex 3D components with nanometric surface roughness. A CNC diamond turning machine and a CNC precision lathe provide capacity for micro-cutting. Two sub-nanometric 3D surface profilers for surface metrology, and a Mitutoyo Coordinate Measuring Machine for dimensional/form metrology measurements at 1µm accuracy. We have invested in our 3D printing (SLS and SLA) capacity and capability including purchasing a Formiga P110 machine (£210k including laboratory refurbishment). Our electrochemical machining laboratory is a unique facility developed from an EU grant in 2010. The machine drills defect-free holes in, for example, single crystal turbine blades provided by Rolls Royce.

The Automotive Habitat Laboratory (AutoHabLab), supported by JLR with £1.1M, is a full-scale automobile simulator with technology that detects behavioural responses enabling designers to hold real-time conversations with drivers when important events occur. The AutoHabLab has proven highly influential towards moving the company's design culture from one of expert-driven technological innovation to one of wide-ranging co-design with users.

Future Plans
The strategic decision by the University to invest in a 10-year programme of refurbishment will continue into the next REF period. Through the UKRI Research Capital Investment Fund we will be prioritising the Aerospace and Environmental Engineering groups to build the research capacity for the recently appointed cohort of ECRs. Within the Energy theme, additional investment in APF is expected and in the UK Centre for Sustainable Energy in Food Chains. For the SDS theme, we are planning investment into a major laboratory for artificial intelligence, especially visualisation.

We are investing in the third phase of BCAST's development with the addition of a new building (1500m^2) to create a scale-up processing hall plus enhanced characterisation capabilities. A total of £16M (£7M, Research England; £6.5M, Brunel; £2.5M industry) for the building (£6.5M) and equipment (£9.5M) has already been committed to this expansion, and is due for construction in 2021-22 (planning permission has been granted).

We have ear-marked £1M for NSIRC, the principal investment being a gas gun for impact testing. In addition, investments in experimental mechanics have been secured: a Hopkinson Bar to characterise high strain-rate behaviour (£250k) plus data acquisition (£105k), and a 10kN electrodynamic testing machine (100Hz) (£110k).

Through an evolving partnership with ZwickRoell we are acquiring a co-designed 250kN servo-hydraulic testing machine operating at -80–1250°C with non-contacting extensometry (£240k). The collaboration enables access to specialist compatible test frames. We anticipate upgrading our heavy structures laboratory with another servo-controlled actuator and load cell (200kN), with bi-axial loading capability.

The Aerospace team have secured £700k for a unique closed-loop wind tunnel (1m^2 cross-section, 60 ms^{-1} jet velocity) designed for aeroacoustics. The changeable working-section will be inside a 5x6x8m anechoic chamber. A double-height laboratory is being converted to accommodate the tunnel and its infrastructure.

We have an ambitious plan to upgrade our electron microscopy suite and to co-locate all infrastructure for materials characterisation in a new building, freeing-up space and increasing our capacity for high-end materials characterisation. We anticipate buying a new FE-SEM, however, already secured is an AFM with conductivity measurement capability (£214k). A new full spectral range UV-Vis-NIR spectrophotometer (£56k) will facilitate our PV and catalysis research. We anticipate investment in our 3 X-ray diffractometers with a new environmental chamber, and a heating stage (for our powder XRDs).

For our high-performance computing facilities, £235K is secured for internal network connections for all hardware at 100Gb/s and external network to/from Brunel up to 100Gb/s for all VOS/applications/users nationally and internationally. Service unification and increasing storage capacity to 3PB improves the capabilities of BCAST, NSIRC, and M&F (especially the aerospace team). Installing two caches will enable very fast and efficient storage access to local clusters and external applications, making the Brunel Data Centre one of the five national centres to offer data to all UKRI application projects. This will make Brunel attractive for SWIFT-HEP investment.

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

The successful implementation of our research and IKE strategies has broadened the range of organisations with which we collaborate, strengthened our international ties, and increased the societal impact of our research. In particular, investing in facilities and giving autonomy to our leading researchers creates an atmosphere where they are able to use their talents to the fullest extent. This institutionally-embedded attitude is generating a culture which is inspiring our current ECRs to strive to become international competitive, and in due course, leading. In our view, this enables us to maintain a high-level of intellectual sustainability with the flexibility for researchers to develop as multidisciplinary thought-leaders.

Contributions to the Research Base

We are members of major multi-institution consortia including:

- UKRI Consortium on Turbulent Reacting Flows, **Xia** (EE), lead, 17 partners.
- Materials and Molecular Modelling Hub Tier 2 national supercomputing centre, **E.Smith** (AMS)
- UKRI Future Composites Manufacturing Research Hub, **Kazilas** (MM).

- UKRI Industry Cluster programme and National Centre for AI in Media Production, **Garaj** (MD).
- EU, Manufacturing of personalized kineto-dynamics parts and products, **Cavallaro** (MD).
- EU, Demonstration of water loops with regenerative business models, **Katsou** (MD).

Major International Collaborations
Cole, **Khan**, **Reid**, **Teodorescu** (SDS) contribute to the CMS experiment at the Large Hadron Collider (CERN), in particular, the Silicon Tracker detector sub-system. Their data analysis exploits GridPP supercomputing facilities. **Kyberd** (SDS) leads our engineering contribution to the international Muon Ionization Cooling Experiment (Rutherford Appleton Laboratory).

Co-operation and Collaborative Arrangements for PGR Training
We are leveraging our PGR partnerships to create research alliances between individuals and group e.g. our relationship with Jiangsu Industrial Technology Research Institute will become a strategic partnership in the coming period. The current focus on precision manufacturing is being expanded to incorporate digital systems researchers.

Interdisciplinarity and Responsiveness to National and International Priorities
An example of our rapid response ability is **Balachandran** (SDS) and his collaborators (Lancaster, Surrey) adapted their point-of-care molecular diagnostic system for SARS-CoV-2 testing. The team is a rare mix of engineers, veterinary virologists and bacteriologists. The on-chip system (Newton Prize nominated) is a low-cost, portable, isothermal molecular diagnostic device for the on-site detection of poultry pathogens (viral and bacterial). It has been developed into a complete platform by Vidiia Ltd, with trial plans by an existing mobile test provider. Approvals registration and licence negotiations are underway.

Also supported through the Newton Fund, **Singh**, **Tassou** (EE), and **Wissink** (AMS) have sustained a collaboration with Egyptian universities on creating energy-positive buildings. The technology developed in the project 'Novel Nano-LiBr based Solar PVT Technology for Poly-generation' (2017-19) was deployed in the 'Sustainable Positive Energy Buildings Using Solar Energy (SuPErB)' project (2019-21).

We created two new international strategic partnerships in this period, with Tampere University (Finland), and FAPESP (universities in Sao Paulo, Brazil). The newly-funded Tampere partnership (£344k, Research England) extends research links and learns from Finland's experience as the top-ranked country globally for industry-academia innovation linkages. The FAPESP partnership has so far yielded five joint research projects, including **Jouhara** (EE) for developing a new heat-pipe based manufacturing line in collaboration with Ervateira São Mateus.

Our Contributions to the Economy and Society
Our research and IKE strategies are challenge-led. Examples of our partnership in major multi-institution consortia exploiting our research capability in contributing to industry-oriented programmes:

- First UK solar EV charging forecourt demonstrator (InnovateUK £7.5M, Brunel £260k), Gridserve (lead), **Axon** (EE).
- Alliance Casting European Development Centre (InnovateUK £9.1M, Brunel £868k) Nissan (lead), **Z.Fan** (MM).
- Reforming of pyrolysis oil for syngas production and conversion into fuels (EU £10.3M, Brunel £689k), Fraunhofer Munich (lead), **Bhattacharya** (SM).

Our activities and schemes facilitating interaction with companies of all sizes create impact with their users, customers, and beneficiaries. In 2017 we established a single online point of access for SMEs to discover resources available across the University, the >900 enquiries to-date relate to research, health and safety, training, and co-innovation projects.

Central Research Laboratory (CRL): is an internationally recognised SME accelerator and the UK's leading programme for product makers and hardware pioneers. Located near campus, the

HEFCE/EU funding (£4M) has leveraged an additional £12M from other sources. The SM, Design, and S&I groups are closely involved. We are transferring maker-space skills to new cohorts of entrepreneurs with extensive prototyping and workshop capacity. The focus is creating innovative solutions for sustainability and the circular economy; aviation, transport and logistics; low-carbon economy; and AI and big data. Operating on a cohort basis, CRL offers unrivalled support for entrepreneurs and early-stage business. The eighth cohort makes CRL one of the longest running UK accelerators. More than 2100 businesses have engaged with CRL. Key indicators for the supported start-ups are:

- 343 start-ups and early-stage businesses using the facilities.
- The 3-year survival rate at >80%, is significantly better than the accepted norm (10%).
- Won investment of £10.5M through angel, grant and crowd-funding.
- Produced >4000 prototypes in the workshops.
- 99 companies have brought 55 products to market, creating >60 jobs.
- Recipients of prizes and bursary worth >£1M, industry awards including the Mayor's Entrepreneur Award, and the Santander Entrepreneur Award (£500k).

Following this success, a joint venture with U+I was formed to build a network of five innovation centres across the UK (over five years) aiming for even wider impact and a more commercially sustainable business model. We won £1.7M from the Research England Development Fund, creating a sustainable ecosystem for hardware start-ups called 'Making the Future Digital', operating alongside our existing facility in a new building. Our University partners for the new project are City, Imperial, RHUL, UCL and UWL. The project has support and endorsements from a wide variety of companies within the region including Heathrow.

Impacting Business by Design (IBbD): Funded by £4.7M from Research England's Connecting Capabilities Fund (with DMU, NTU). IBbD addresses government objectives of improving business productivity and competitiveness by transforming their ability to commercialise design innovation and bring new products to market. Adoption of professional design capabilities is incentivised through an innovative 'deferred repayment grant', whereby design fees incurred during the project are repaid only when the company reaches a significant level of sales revenue. We have completed 55 projects spanning MedTech, FinTech, sports equipment, industrial tools, and personal protective equipment.

Business Development Managers (BDM): (two in UoA12), discovering collaborative opportunities by addressing defined needs of companies. HEIF funding supports the BDMs to participate in important national industry shows and conferences, leading directly collaboration with >20 companies, including BAE Systems. Examples of BDM-initiated projects include:

–Haes Systems (fire detection and alarm products). **Nilavalan** (SDS) won £196k for a KTP project applying wireless technology to better integrate their products with third party systems giving Haes a competitive edge over other suppliers.

–Smiths Detection established a unique research facility at Brunel, incorporating an industrial-scale airport scanner to develop new image analysis techniques to improve the reliable detection of threats in electronic devices in hand luggage (**Mousavi**, SM)

Innovation Voucher Scheme: promotes collaborative innovation between Brunel and UK SMEs by offering vouchers for the costs of accessing facilities and staff. The company contributes an equal value in cash/kind such as staff time, materials or equipment. All themes have taken part, with 22 projects completed in engineering to-date. Examples are:

- Natural and nature-based solutions for coastal defence (at Dover, UK), SAM Design & Construction Ltd (**Heidarzadeh**, EE).
- Thermal modelling of vaccine carriers, Ideabatic Ltd **Wissink**, AMS).
- Home energy efficiency analysis software, Thermafy Ltd (**Grant**, MD).

One example of creating *international* impact is the low-cost solar-electric kitchen extraction fan for developing countries (**Singh** (EE) with EnSo Impact). Successful exploitation of the voucher (2017/18) resulted in winning an Energy Catalyst grant, 'Solar Energy for Cleaner, Safer Kitchens in Kenya' (InnovateUK, £223k).

Commercialisation Activities
We maintain a pipeline of around 30 commercialisation projects, with typically 20 new disclosures a year, from which we have generated 13 active licences and launched four Brunel spin-outs which are supported by £1.2M of external commercial income. In this REF period, 31 academic staff conducted 104 consultancy contracts. Brunel also took equity in return for IP in an external start-up. Examples of our current licence agreements and patents are:

- Niobium grain refiner technology to CBMM for 5 years (**Nadendla** , MM).
- Capacitively coupled cables for transmission and distribution of electrical power with Enertechnos Ltd (**Darwish**, EE).
- Active Refrigeration Shelf with Thermal Storage system, patents in many countries, including China (**Jouhara**, EE).
- Photo-active polymer sheets for horticulture applications, patent (**Fern** and **Silver**, MM).
- RegenEBD, regenerative braking system optimised for buses and coaches and licenced to Yuchai (**H.Zhao**, EE).

We support staff in creating impact whilst working towards commercialisation. Some of our current (and future) ICS resulted from our strategic partnerships, others have emerged from the long-term support for research areas. An example of the latter is the polymer replacement ICS (**Taverdi**, MM). **Ivanov's** (SM) electrochemical machining device, initially funded through an EU grant, has been applied to precision applications in aerospace, biomedicine, sensors, and automotive. For example, the first prototype machine is sited at Sonplas GmbH (Germany) is machining micro-holes for advanced fuel injection systems for BMW. An important emerging application of **Fern** and **Silver's** (MM) electroluminescent materials work (funded by InnovateUK) is the prototyping of large area photo-active polymer sheets for horticulture polytunnels. The photobiological theories and absorber materials underpinning this technology have been developed by Brunel and another leading UK university in partnership with UK industry. Field tests are showing that this is providing levels of control comparable to chemical pesticides. Investment of £1.1M by our strategic partner JLR (the largest UK manufacturing investor in R&D) created the AutoHabLab and a toolkit of human centred design methods for use with automotive system, directly leading to >50 JLR designers being trained in strategies to improve the rigour of their design processes (**Giacomin**, SM).

Indicators of Wider Influence
We published approximately 3560 articles in peer-reviewed journals (Web of Science) many in collaboration with industry or international collaborators. A total of 17 staff are members of the EPSRC Peer-Review College. **Pei** (MD) is a Member of the EPSRC Early Career Forum in Manufacturing Research.

Our staff have been recognised through elected Fellowships and other personal honours, some highlights are:

- Four elected to FREng: **Nandi** (SDS, 2014), **H.Zhao** (EE, 2015), **Lingwood** (AMS, 2019), and **Rogers** (EE, 2020, RAE Visiting Professor).
- **X.Wang** (EE): UKRI Future Leader Fellowship, 2020.
- **Usman** (EE): Individual Marie Curie Fellowship, 2019.
- **Soltani** (MD): RAEng Exceptional Talent Programme, 2017.
- **H.Zhao** (EE): Honorary Professor, Jilin University, China.
- **Karayiannis** (EE): Fellowship of the World Society of Sustainable Energy Technologies for his outstanding contributions to science and technology.
- **Jouhara** (EE): Honorary Consul, Wroclaw Univ. Science and Technology, Poland, 2018.

Examples of prizes and awards:

- **Scamans** (MM): Gold Medal, IoM3, 2019.
- **Simons** (MD): Trustees Medal, IChemE, 2020.
- **H.Zhao** (EE): Herbert Akroyd Stuart Prize, IMechE, 2015 and 2017.
- **Nadendla** (MM): Charles Hatchett Award, IoM3, 2016.
- **Ceschin** (EE): Bronze Medal, Brazil Design Awards, 2018.

- **Darwish** (EE): winner, Energy and Environment Rushlight Award for 'Capacitively Coupled Cables for Transmission and Distribution of Electrical Power', 2019.
- **Tyacke** (AMS): "Best use of ARCHER" (national supercomputer), 2017.
- **Jouhara** (EE): Energy, Environment and Sustainability Group Prize, IMechE, 2017.
- **Abbod** (SDS): Best Paper, IEEE Conference on Computational Intelligence in Bioinformatics and Computational Biology, Niagara Falls, Canada, 2015.
- **Angelides** (SDS): Best Paper, IEEE 7th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference, New York, USA, 2016.
- **Karayiannis** (EE): Best Paper, 4th International Conference on Multiphase Flow and Heat Transfer, Rome, 2019.

This UoA has won six Royal Academy of Engineering Distinguished Visiting Fellowships: Professor Mingfa Yao (Tianjin University, China) hosted by **H.Zhao** (EE); Professor Weihua Zhang (Southwest Jiaotong University, China) hosted by **Meng** (SDS); Professor Zhimin Wu (Dalian University of Technology, China) hosted by **X.Zhou** (AMS); Professor Guo-Qiang Li (Tongji University, China) hosted by **Z.Huang** (AMS); Dr Hua Chen (National Laboratory of Engine Turbocharging Technology, China) hosted by **Pesyridis** (EE); and Professor Zongjin Li (Hong Kong University of Science and Technology, HK) hosted by **X.Zhou** (AMS).

We have also won seven Royal Academy of Engineering Visiting Professorships: Lucy Rogers (Makertorium Ltd) hosted by **Gratton** (EE)**,** Alexandra Knight (Amey Strategic Consulting) hosted by **Collins** (EE), Richard Pearson (BP) hosted by **H.Zhao** (EE), Steve Kaye (Anglia Water) hosted by **Katsou** (MD), Arthur Ekwue (Jacobs Engineering Inc) hosted by **Taylor** (EE), Vincent Glancy (Arup) hosted by **Katsou** (MD), and Paul Tymkow (Hoare lea LLP) hosted by **Jouhara** (EE).

Kolokotroni (EE) won three Rutherford Fellowships to host Australian Visiting Academics: Dr Wendy Miller (Queensland University of Technology), Dr Jin Rose Woo (RMIT), and Dr Fengji Luo (U. Sydney).

Exemplars of other indicators of influence:
Visiting Professorships:
Kolokotroni (EE): Hunan University, China.
Jouhara (EE): Wroclaw University of Science and Technology, Poland.
Lingwood (AMS): KTH Royal Institute of Technology, Sweden.
Stolarski (AMS): Tokyo University of Science, Japan.
Wrobel (AMS): Pontifical Catholic University of Rio de Janeiro, Brazil.
Assadi (MM): Helmut Schmidt University, Germany.
Dai (MM): University of Adelaide, Australia.
Eskin (MM): TU Delft, Netherlands.
Al-Raweshidy (SDS): Yuan Ze University, Taiwan.
Nandi (SDS): University of Calgary, Canada.
Atherton (MD): University of Modena and Reggio Emilia, Italy.
Pei (MD): University of Canterbury, New Zealand.

International Grant Review
Axon (EE): RCN (Norway), NWO (Netherlands), CONACYT (Mexico).
Ceschin (EE): MIUR (Italy).
H.Zhao (EE): SNSF (Switzerland).
Alfano (AMS): QNRF (Qatar).
Angelides (SDS): NSF (USA).
Nilavalan (SDS): Mitacs, Canadian Network of Centres of Excellence.

Professional Service
Heidarzadeh (EE): elected, Secretary General, International Tsunami Commission, 2019.
Taylor (EE): CIGRE Technical Committee on Information Systems and Telecommunication.
Lingwood (AMS): Trustee, Daphne Jackson Trust.

Cavallaro (MD): American Society for Testing and Materials Technical Committee on Additive Manufacturing; and President, International Society for Prosthetics and Orthotics Italia, 2015-2020.
Evans (MD): Chair, IEEE Technical Committee, Technology and Engineering Management.
Mynors (MD): Engineering Professors' Council, Research, Innovation and KT Working Group.

Significant Editorial Roles
Karayiannis (EE): Proc. IMechE Part C: Journal of Mechanical Engineering Science.
Jouhara (EE): International Journal of Thermofluids (Elsevier).
Zobaa (EE): Technology and Economics of Smart Grids and Sustainable Energy (Springer).
Eskin (MM): Journal of Alloys and Compounds (Elsevier).
Abbod (SDS): Engineering Applications of Artificial Intelligence (Elsevier).
Boulgouris (SDS): IEEE Transactions on Image Processing.
Pei (MD): Progress in Additive Manufacturing (Springer).
Lai (EE): Secretary, IEEE Smart Cities Publications Committee.

Notable Conference Contributions
Lai (EE): Organiser, IEEE SMC workshop, Canada (2017), Japan (2018).
H.Zhao (EE): Chair, 14th International Conference on Present and Future Engines for Automobiles, Hokkaido, Japan, 2017.
Sadka (SDS): Co-chair, Emerging Technologies in Biomedical Engineering and TeleMedicine, Doha-Qatar, 2018.
Atherton (MD): Organiser, 16th International Design Conference, Dubrovnik, Croatia, 2020.

Plenaries and Keynotes
Karayiannis (EE): 16th International Heat Transfer Conference, Beijing, 2018.
H.Zhao (EE): 13th Engineering Foundation International Conference on "Engines, Present and Future, New York, 2015.
Alfano (AMS): Croatian Society of Mechanics, 2018.
Agius (SDS): Design Research Workshop, Taipei, Taiwan, 2019.
Nandi (SDS): IEEE Engineering in Medicine and Biology Society, 2018.