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| Institution: Teesside University |
| Unit of Assessment: 12 Engineering |
| 1. Unit context and structure, research and impact strategy |

Unit context and structure

Our General Engineering unit (78.6 FTE) is situated in the School of Computing, Engineering and Digital Technologies (61.6 FTE) and draws in expertise from the School of Health and Life Sciences (13 FTE) and Teesside University Business School (4 FTE). We organise our research through two research centres and three innovation centres.

The Centre for Sustainable Engineering (led by Short) includes 53 FTE staff, 10 researchers, seven graduate tutors and 55 research students. Research activities focus on the decarbonisation of industry and society, using engineering approaches spanning the disciplines of chemical and materials engineering, civil engineering, electronics, instrumentation and contrail engineering and applied digital technologies such as building innovation modelling (BIM), smart energy and bitcoin. The centre encompasses interdisciplinary and transdisciplinary research with a broader set of researchers including in business, computing, and the social sciences. The centre's research is organised under four themes: Construction Innovation and Research (led by Dawood N and Rahimian); Energy Conversion, Management and Control (led by Short and Al-Greer); Hydrogen Engineering and Decarbonisation Technologies (led by Krishnan and Ahmed); and Sustainable Materials and Circular Economy (led by Hamad and Hughes).

The Centre for Digital Innovation (led by Hossain) includes 25.6 FTE staff, four research associates, four graduate tutors, and 28 research students. Research activities address the growing demand for artificial intelligence (AI) and its applications; and digital technology research to tackle economic, societal and contemporary technological challenges using computational methods, computer and software engineering, computer vision, healthcare technologies, information engineering, intelligent and adaptive systems, and machine learning. The centre takes a multidisciplinary collaborative approach drawing on engineering applications in areas such as biosciences, business, education, health and social sciences. The centre's research is organised under three themes: Digital Engineering for Health and Wellbeing (led by Angione); Gaming and Immersive Technologies (led by Pandit); Information Systems and Security (led by Chang).

The industry-facing activities at our research centres are supported by three innovation centres, where we work in formal partnership with independent research and technology organisation TWI to undertake collaborative research with its industrial membership base. In 2017, we established the Healthcare Innovation Centre (led by Ali) to develop health technologies. In 2020, two further formal collaborations were agreed: the Industrial Decarbonisation and Hydrogen Innovation Centre (IDHIC, led by Pinedo-Cuenca), and the Circular Economy and Recycling Innovation Centre (CERIC, led by Hughes). Our innovation centres are part of TWI's innovation network, which includes 12 innovation centres, the National Digital Catapult and the National Structural Integrity Research Centre.

The multidisciplinary nature of our research base allows staff to collaborate on areas of interdisciplinary focus such as digital and analytical technologies for forensic science, archaeology and anthropology. Interdisciplinarity is supported across research centres, between research themes and through the university's three interdisciplinary grand challenge themes (creating vibrant, cohesive and resilient and societies; forging a smarter, greener industrial economy; and shaping the future of health, care and wellbeing), which drive institutional research priorities aligned to regional growth, the UK's industrial strategy and the UN's sustainable development goals.

Research and impact strategyResearch strategy

Our 2014 research strategy set out to: facilitate internationally led, applied research through strategic partnerships and research collaborations; enable a supportive research culture and a team approach; and maximise research impact on business, the environment and society.

Since 2014, we have increased critical mass to strengthen the research environment, as demonstrated by an increase in research active staff (from 13 FTE in 2014 to 78.6 FTE in 2020), 55 FTE staff appointments and £3.3m invested in studentships.

Engineering has created a supportive research culture and a team-working approach for both staff and postgraduate students, as evidenced by: a 90 per cent increase in average annual postgraduate completions since 2014 (from 5.5 in REF 2014 to 10.4 in this period); improved governance of research activities through our research centres; the appointment and development of research centre leads; and the delivery of a new Researcher Development Programme (RDP). (See section 2.)

We have facilitated interdisciplinary working, by engaging with the university's grand challenge themes and creating interdisciplinary research themes within research centres. For example, the grand challenges enabled a collaboration between Dawood N and Van Schaik (Centre for Applied Psychological Science) resulting in the ESRC project, Putting People at The Heart of Future Social Housing and Design And Manufacturing (UCL CID-302511). Collaborations across the Construction Innovation and Research and the Energy Conversion, Management and Control Research themes also led to two EU projects, the €10.7m Renewable Energy For Self-Sustainable Island Communities – REACT (grant agreement 824395) and the €5.1m Demand Response In Blocks Of Buildings – DR-BOB (696114) projects, which bring together insights from engineering and the social sciences.

Our industry collaborations have been strengthened by investing in support mechanisms and facilities, as evidenced by: £0.9m investment in three TWI innovation centres; the creation of a University Enterprise Zone, along with renewed investment of £2m in DigitalCity, a longstanding business innovation programme to facilitate SME R&D; £12m European Regional Development Fund (ERDF) and Tees Valley Combined Authority (TVCA) investment in the Net Zero Industry Innovation Centre, which is scheduled to open mid-2022; and £2m ERDF and TVCA investment in an Industrial Digitalisation Technology Centre, planned to open early in 2021.

We have increased research grants and contract income (RGCI) to support industrial and international collaborations, as evidenced by a 57 per cent increase in annual RGCI (from £0.8m in REF 2014 to £1.3m in this period). Forty-three per cent of our RGCI is from international collaborations. Forty per cent of our RGCI is from contract and collaborative industry research (see section 3).

We have facilitated international collaborations, as demonstrated by 50 per cent growth in co-authorship with researchers in other countries from 2014 to 2020. Our average international co-authorship is above average, at 58.7 per cent of publications over the period, compared with the UK average of 52 per cent (based on SciVal reports).

Impact strategy

Our 2014 impact strategy aimed to:

- focus on applied and collaborative research to deliver research of use to partners and stakeholders

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- embed impact as part of the research design process to ensure it is sufficiently resourced, managed, and evaluated
- maintain research partnerships beyond the lifetime of projects to support the embedding of impact and to address emerging challenges
- increase our focus on knowledge exchange to facilitate the application of research and to identify, protect and commercialise intellectual property.

Since 2014, we have delivered demand-led R&D projects to address industry challenges in the areas of building information management (BIM) and digitalisation through seven Knowledge Transfer Partnerships (KTP) with architectural, engineering and construction companies. Here our research on advanced multi-constraint and multi-dimensional visual construction planning and coordination (Dawood N, Dawood H, Kassem M, Patacas J, Rodriguez S) has led to new products and international markets for the UK companies involved. Work with Ryder Architecture has led to the firm acquiring 500 new clients in 19 countries for its BIM for FM services, increasing its turnover by £1,000,000 per annum. Our work with Hodgson Sayers' has led to it becoming a Tier 1 Contractor and securing contracts worth £4.7m since 2016, transforming its business culture. Our work with Sotech, a metal rainscreen cladding manufacturer, has led to it doubling its turnover from £7m to £14.5m. [ICS1]

Sustained relationships with UK food manufacturers have led to the implementation of systems engineering solutions to enhance monitoring and control for quality improvement. [Text removed for publication.] [ICS2]

Research on digital processes and asset engineering information sharing has led to the development of novel digital technologies and processes for the management of information flows throughout the entire life cycle of complex and heavy engineering and construction assets for two UK companies. Researchers in asset management, digital twins, and digitalisation (Dawood N, Dawood H, Patacas, Vukovic) have transformed the market base of Datum360 and Unasys. For Datum360, research has contributed to a growth in turnover from 2018 to 2019 of 23% to GBP2,124,000, with international sales growing from close to zero to more than 35% of revenue. For Unasys, the research has expanded their client base and business portfolio and led to them securing funding from the Oil & Gas Technology Centre in Aberdeen for a project worth GBP650,000. [Text removed for publication.]

We have undertaken a series of EU-funded, impact-focused collaborative research projects to generate a step change in energy management, increasing awareness and uptake of demand-response (DR) technologies. In three EU collaborative projects from 2008 to 2020 (Short, Crosbie, Dawood N, Rodriguez, Vukovic) we undertook partnership working with a diverse range of stakeholders across Europe to raise awareness of DR technologies at four demonstration sites. The research has led to commercial product development [text removed for publication], optimisation and energy savings (Porvoon Energia), and changes to working practices of those working in the smart energy sector (Duneworks, Nobatek). [Text removed for publication] [ICS5] .

We have invested ERDF, Higher Education Innovation Fund (HEIF) and Connecting Capability Fund grants to develop the commercial awareness and innovation skills of staff and students. Spin-out Anasyst Ltd (incorporated August 2013) was set up on the basis of an optical detection technology patent (US8325342B2, Ali), using HEIF funding. The company has been involved in a €1m European Commission research for SME programme (Cavity Enhanced Microarray As An Ultra-Sensitive Tool To Aid Sepsis Diagnosis, 2014-16) and is currently working with a number of other supply partners (Wideblue, BMG Labtech, Nehir Biyoteknoloji and Opaal Agency) to commercialise the technology.

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We are participants in a £3.9m Intensive Industrial Innovation Programme (IIIP), funded by ERDF and the region's five universities, to support up to 48 of the region's SMEs to develop new services and products for the market, supported by dedicated PhD research students. Using Research England Connecting Capability Funding, we have joined the Northern Accelerator Programme to provide enterprise training for academics, proof-of-concept support, a network of entrepreneurs embedded in the earliest stages of spin-out companies and to establish a North East University Investment Fund to support research-based spin-outs in the region.

We have also sought to expand our impact by informing policy and practice and undertaking targeted public engagement work. Our research on 3D modelling, visualisation, and forensic archaeology has led to the development of new and revised guidelines and standards for the Archaeology Data Service and the British Association for Biological Anthropology and Osteoarchaeology. This research has also enabled enhanced public understanding of archaeology (York Archaeological Trust; Durham Museum of Archaeology, Vindolanda) and the engagement of new audiences with archaeological objects (Channel 5). [ICS6]

Engineering and social science insights have been brought together to support evidence-informed policy on climate change and decarbonisation. For example, research on energy efficiency (Crosbie) was cited in two 2014 reports by the UK Department of Energy and Climate Change (Further Analysis Of The Household Electricity Survey: Light Study Final Report and How Heating Controls Affect Domestic Energy Demand: A Rapid Evidence Assessment) as well as the Department for Business, Energy and Industrial Strategy's 2016 Scoping Review of Heating Controls. Research on waste management (Ali) has been cited in a UN report, Resource Efficiency: Potential And Economic Implications (2017). Research on digitisation in the construction industry (Dawood N, Kassem) led to Kassem being appointed by the Ministério do Desenvolvimento, Indústria e Comércio Exterior and the Ministério do Planejamento, Orçamento e Gestão (Brazil), to work with Prof. Sergio Leusin to conduct a structured examination and illustration of BIM in the EU and in Brazil. The report was jointly discussed with Brazilian policymakers to produce a set of conclusions and recommendations for BIM diffusion in Brazil. Working closely with Middlesbrough Environment City, our research on energy adoption and societal attitudes to energy consumption (Crosbie) was used to support the evaluation strategy and subsequent work of the sustainability strand of One Planet Middlesbrough.

We have initiated a series of global challenge international projects to support clean water and sanitation, supported by the quality related (QR) Global Challenges Research Fund. For example, research on groundwater remediation using nanotechnology (Pak) is bringing together representatives from key industries, governmental agencies, and academia to develop a plan and a technical design for implementing the first pilot-scale nanoremediation case study in Brazil and to evaluate its effect on public health. Research on membrane technology (Ahmad) is being undertaken with COMSATS University and The Urban Unit in Pakistan to develop a complete system for the fabrication and testing of membranes for drinking and wastewater treatment.

Future research strategy

In 2020, the university published its corporate strategy to 2025, Ambition Delivered Today, which focuses on making a difference to the lives of people and driving forward the success of businesses and the economy. As a civic university and anchor institution, our research strategy for 2020-25 places engagement at the heart of the research process, so that our research activities influence the wellbeing, productivity and prosperity of the region, nation and wider world.

Our research centre themes are aligned to grand challenges set out in the government's industrial strategy (Artificial Intelligence and Data, Ageing Society, Clean Growth, and Future of Mobility), EPSRC themes (Energy, Engineering, Living with Environmental Change, Digital Economy,

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Information and Communication Technologies, and Healthcare Technologies) and the Tees Valley Combined Authority's regional investment priorities (Healthcare and Life Sciences, Digital and Creative, Energy and Renewables). We have six strategic priorities for 2020-25.

- We will increase research capacity by: investing in staff posts, securing external funds for fellowships and developing existing staff; investing in PhD studentships using QR funding and leveraging external industry funding; and increasing the proportion of research leaders (professors and readers) from 13 FTE to 25 FTE by 2025 to provide leadership to the 34 per cent of current early career staff. We will prioritise growth in the areas of chemical engineering and materials (specifically catalysis technologies for energy conversion and reprocessing), electrochemistry (batteries, fuel cells), and energy informatics to strengthen our focus around decarbonisation, green energy and industrial resource efficiency. We will invest in digital engineering, AI, cybersecurity, and immersive technologies targeting research at the manufacturing and healthcare sectors.
- We will develop capability by investing in facilities and technical staff to support our expanding focus on decarbonisation and environmentally sustainable industries through a £12m Net Zero Industry Innovation Centre to open in 2022 which will include laboratories for fuel cells, electrolysis, batteries, intelligent energy systems, efficient manufacturing process development and end of life technologies including waste pyrolysis and depolymerisation. This will also house two of our TWI Innovation Centres IDHIC and CERIC (£600,000 investment 2020-22), and our £2m Industrial Digitalisation project commencing in 2021. A £13m investment in our Digital Life Centre, to open in 2022, will support our research, teaching and commercial training in digital technologies. It will include smart labs, digital art studios and a collaborative environment for interdisciplinary research. Our approach to creating Digital Life systems and services for the future will focus on themes of ethics, sustainability, accessibility, inclusivity and diversity and foster the notion of the 'digital citizen' to engage and educate society on the responsible and effective use of digital technologies.
- We will facilitate interdisciplinary research to expand the expertise and approaches of the unit to address complex research questions through pump-priming early-career researchers (ECRs) to engage in small-scale projects and publish interdisciplinary outputs aligned to the grand challenge themes and supporting staff to participate in externally funded interdisciplinary projects.
- We will expand our researchers' international and industrial networks by using QR and HEIF funding to support international sabbaticals, industrial staff secondments and collaborative studentships.
- We will promote a responsible culture that: delivers best practice in relation to equality, diversity and inclusion (EDI) in recruitment, mentoring and promotion practices; recognises and rewards team research; embeds policies on research evaluation (aligned to the San Francisco Declaration of Research Assessment, DORA) and research data management; promotes the benefits of open research on integrity and engagement; and improves support for developing researchers using improved personal development plan and review (PDPR) processes, ECR mentoring and our researcher development programme.
- We will maximise research impact and deepen engagement by: involving communities and industrial stakeholders in the design, delivery and communication of our research, especially in relation to AI and the regional decarbonisation and green energy agendas; establishing public engagement fellowships; developing the skills of staff and students by implementing the university's Impact Framework, which outlines the behaviours, skills, and mechanisms for advancing research impact; and supporting innovation and commercialisation through

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participation in the Northern Accelerator and the creation of a university subsidiary company Teesside University Enterprise and Innovation to effectively commercialise the research of staff and students.

Interdisciplinary research

We understand today's societal challenges are complex and demand expertise from various perspectives to solve them. Over the period we have supported researchers to develop their interdisciplinary practice through our research centre themes and wider university grand challenges, as well as through participation on external interdisciplinary projects.

Our ECRs are encouraged to apply for seed funding from the university's grand challenge scheme, which supports the initial development of their projects, including employment of research assistants. Both Angione and Han received grand challenge funds that led to the development of larger projects, including: a US\$225,000 (£160,000) Future of Life Institute grant for Han (Incentives for Safety Agreement Compliance in AI Race) to study incentives for ensuring safety compliance in the context of the technological innovation, with researchers from economics, health and psychology disciplines; and a £402,000 Innovate UK funded project (Quickfit, Quick Fitting Of Prosthetic Sockets For Above-Knee Amputees, 133657-9933) working on the interaction between biomechanics, sensors and smart design for prosthetic limbs involving Angione.

Our grand challenge themes have also provided a forum for collaborations involving various disciplines across the university that have led to externally funded projects, such as Crosbie's British Academy project, What is in A Meter? Working Towards Efficient, Socially Inclusive and Environmentally Sensitive Energy and Water Infrastructures In The Global South, (UWB190097), run in collaboration with Newbury-Birch at the Centre for Social Innovation in the School of Social Sciences, Humanities and Law.

Our TWI partnership creates opportunities to for staff to engage with up to twelve innovation centres in the TWI innovation network. For example, the Innovate UK Intelliscan project (An Enhanced Artificial Intelligence Breast MRI Scanning System, 104192-4901, Ali) is a collaboration between the Healthcare Innovation Centre and the Brunel Innovation Centre that uses a combination of advanced image processing and AI to develop a breast MRI scanning system for use as a diagnostic decision-support tool for radiologists.

Open research

We are committed to responsible research and to ensuring the highest standards of integrity in research. We support researchers to make their research outputs and data available to enable the replication and verification of results. To do this we have adopted the FAIR principles to ensure our data are findable, accessible, interoperable, and reusable. For example, Pak published the data accompanying her papers in PNAS and Nature – Scientific Reports (see REF2) comprising images, raw and processed data. The data for the Nature paper was published in Nature – Scientific Data in 2019 (<https://doi.org/10.1038/sdata.2019.4>) and that for the PNAS paper is available at https://figshare.com/articles/dataset/X-ray_computed_tomography_images/12053607/1. A key output from the IDEAS project (<https://doi.org/10.1016/j.apenergy.2016.04.052>, see REF2) made use of a novel dataset for CHP heat and electricity demands and real-time fuel prices. This was made available for non-commercial purposes, and multiple requests have been received to use the data by research teams in Europe.

Throughout the period, our unit has contributed to the development of the university's policies and systems for open research. For example: Qin was part of the project board to implement Pure in 2018, and contributed to the refresh of the Research Data Management Policy in 2019; Dawood N

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contributed to the refresh of the open-access (OA) policy in 2020; and Rahimian sits on the institutional Project Board for the Mendeley Data System.

Researchers have been encouraged to engage with open dissemination within their own research networks. For example: the MemLock smart fuzzing system proposed by Qin and co-authors (published at ICSE 2020) has helped detect security-critical software vulnerabilities (15 of which have been recorded in the publicly disclosed database of common vulnerabilities and exposures, CVE). The MemLock system has been made open source to allow its wide adoption and application in software vulnerability detection by end-users from both academia and industry.

Through the university's RDP and research centre seminar series, we have delivered training on OA, research data management, and the responsible use of metrics. We have encouraged staff to attend research briefings on open science from Dr Paul Ayriss (Chair of Liber's Citizen Science Working Group) and on the responsible use and limitations of bibliometrics from Professor Mike Thelwall (Professor of Information Science at the University of Wolverhampton, member of the Forum for Responsible Metrics).

Until recently, staff managed their research data within their own project data management plans ensuring data requiring retention were stored in appropriate off-site repositories (in line with the partner/funder terms and conditions) and internal records maintained to enable access. Supported by an updated Research Data Management (RDM) Policy, we are moving to sharing our data more effectively through the implementation of the open, cloud-based platform Mendeley Data. A local pilot of the new system is underway to upload data sets. The new system and training will be rolled out in the first half of 2021, followed by the development of reports to monitor our open science activity.

Research integrity, ethics, and governance

We manage research integrity and ethical approval through School Research Ethics Sub-Committees, (SRESC) overseen by the University Research Ethics and Integrity Sub-Committee (UREISC).

At an institution level, staff and postgraduate students attend research integrity and ethics training programmes. New staff are made aware of the university's principles and procedures set out in the Framework and Code of Practice for Ensuring Research Integrity during their induction. From August 2021, it will be mandatory for staff to attend workshops to update their awareness of legislative requirements and best practice in relation research integrity and ethics within a three-year time frame. The HR team will inform associate deans and SRESC chairs which staff require refresher training.

Staff in the unit deliver ethics training to students on the economic, social and environmental ethical implications of engineering research and how these might be mitigated through the research design process (Hughes, Crosby). The training draws on the Engineering Council and Royal Academy of Engineers Joint Statement of Ethical Principles (2017) and the EPSRC's responsible research and innovation framework, AREA (Anticipate, Reflect, Engage and Act) to guide engineering practice and behaviour.

Through our seminar series, external projects, and wider networks, we encourage colleagues to explore the wider ethical issues related to new technologies and their impact on society and the environment, including issues such as the transparency of machine learning and algorithms, and the environmental impact of computational power needed for big data and reproducibility. For example, Han's FLI interdisciplinary project is exploring the normative and social impacts of AI to assess which technologies and domains require regulation to ensure AI advancements do not create ethical or social issues. His insights are proving useful for staff and students via his

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seminars on the responsible development of AI informed technologies. In addition, Short delivered an invited talk at the UK-Asia Seeding STEM summit 2020 on how technology is shaping and changing society.

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| 2. People |
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Staffing strategy and staff development

We recognise our staff as our most important asset and our staffing strategy supports the university's commitment to attract, retain, develop and reward staff, and to enable all staff to achieve their full potential in their role and career.

Our strategy for staff growth, together with our research policies around recruitment, retention and reward, have enabled significant growth for future sustainability: 55 FTE staff (70 per cent) have been appointed within the census period; 13.6 of our FTE staff (17 per cent) who were not submitted previously have developed their research and are now identified as having significant responsibility for research (SRfR); 10 of the 13 FTE returned in 2014 remain; just two staff left for new posts and one retired.

We have targeted our recruitment in the areas of: artificial intelligence; building information modelling and digital construction; civil engineering; control systems and automation data analytics; cybersecurity; power systems and energy; energy informatics; and sustainable materials.

The creation of new posts combined with the university's academic careers framework and progression policy has supported the promotion of 19 staff across the period, as follows: five from research associate or research fellow to lecturer; two from lecturer to senior lecturer; four from senior lecturer to reader; two from senior lecturer to principal lecturer; one senior lecturer to enterprise fellow; three from reader to professor, including one subsequent promotion to associate dean; one principal lecturer to acting associate dean; and one professor to associate dean. Two staff within the unit completed a PhD over the period (Hughes, subsequently promoted to enterprise fellow, and Shadman-Pajouh, a senior lecturer).

Staff development strategy

Our staff development approach is aligned to the UK's Concordat to Support the Career Development of Researchers, and to the university's concordat implementation and enhancement action plan (linked to the university's HR Excellence Award). Our research centre leads assign mentors (readers and professors) to researchers to provide advice and guidance on developing their network, career planning, professional development, project design, bidding, publishing, and public engagement and impact activities.

During the PDPR process, or the initial development plan (for new staff), staff discuss their research and impact plans, development needs, and longer-term career aspirations with their head of department and research centre lead.

We have engaged actively with the university's RDP, which provides support for researchers at all stages of their research career including those in leadership roles. It includes postgraduate, ECR, mid-career and leadership programmes and short workshops covering research methods, supervision, evaluation, open science, metrics, impact, and funding. These are supplemented further by a weekly seminar series, where internal and external speakers are invited to present their research.

Over the period postdoctoral researchers and postgraduate students have been provided with opportunities to contribute to the research culture and to teach. For example: Vukovic played a key role in supporting the DTA programme before moving to an academic contract in 2016 and Dawood H supported the delivery of funded projects and postgraduate supervision and was

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promoted into a lecturer role in 2020. Of our current postdoctoral researchers, Arma works with Han on the Future of Life Institute project and supports the PhD student on the evolutionary game theory research; and Williams has been delivering teaching on control systems.

Because we have a high proportion of new and early career staff, we have prioritised leadership development of senior staff during the past three years to ensure we have the leadership capability to support the careers of our developing researchers. Five members of staff (Angione, Chen, Crosbie, Dawood H and Islam) were nominated to participate in the Research Leadership Programme designed for those in, or aspiring to be in, leadership roles. Subsequently, Angione, Crosby, Islam and Dawood H, were promoted. Two staff members (Hossain, Short) attended the research centre leads programme, which allowed a cohort of senior researchers to support one another in the development and delivery of research centre strategies, build a research leadership network across the institution, and to reflect on and consolidate their own leadership style.

Staffing and recruitment strategy

Post 2014, our staffing strategy set out to improve our sustainability and vitality by increasing and diversifying our staffing base and creating a vibrant and supportive research culture. In 2014, we submitted a select return of 13 FTE. This was made up of three professors (23 per cent of our total staff), one senior manager (8 per cent), two readers (15 per cent), seven senior lecturers (54 per cent) and two early career staff. In line with our aspiration to improve sustainability and the university's 2020 vision (to increase the proportion of research active staff), our staff base has grown more than sixfold (605 per cent) to 78.6 FTE with SRfR.

Our recruitment strategy set out to increase the proportion of staff at lecturer and senior lecturer level and ensure ECRs were well represented among our lecturers. Among the 55 new members of staff, 27 (49 per cent) are ECRs. The proportion of ECRs has increased from 15 per cent (two FTE) in 2014 to 34 per cent in 2021, which provides a good basis for future sustainability and succession planning. The seven FTE at senior lecturer level submitted in 2014 represented 54 per cent of a small submission. In 2021, 71 per cent of the staff to be submitted are at senior lecturer and lecturer level.

Alongside our investment in new posts, we appointed 13 graduate tutors over the period. The posts include protected time to undertake a PhD alongside some teaching experience and are designed to produce home grown, research-active academics to increase the research base. Six of these staff are on track to complete PhDs within the next year. They will move to a lecturer contract and be allocated on-going research time to support the next stage of their career development.

Four of our new appointments have been made at professorial/dean level (Chang, Hossain, Jayne, Montague) and four at reader/principal lecturer level (Angione, Chen, Han, Rahimian). Angione and Han, who joined the unit in the post-REF 2014 period as ECRs, were promoted to reader (in 2019) because of the relationships, outputs and grants they generated in the current REF period.

Our staff investment and development plans supported the progression of research staff through to permanent academic posts. Five of our research assistants and fellows have secured academic contracts and are part of this submission (Dawood H, Ennis, He, Rodriguez, and Vukovic). Support for researchers on fixed-term contracts is outlined in the institutional statement (see REF5a, p.6).

We recognise and reward the research successes of staff and students by: celebrating their research outputs, conference contributions, public engagement activities, grants and other achievements via the school's monthly Good News Stories circular and via the University Update newsletters; promoting their research through social media and news channels (supported by our corporate communications team); nominating staff for the university's Research Performance Star award (Al-Greer was awarded this in 2019 for founding a battery laboratory); and using the academic career pathways and progressions policy. Nine promotions to reader/enterprise

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fellow/professor have been achieved in the period and in 2020 we revised the criteria and policy to support promotion to senior lecturer.

In addition, we incentivise staff to engage in research by competitively allocating £70,000 of seed-corn research funding a year, for staff to develop ideas and to obtain preliminary data to support large, external funding applications and/or publish journal papers. ECRs are prioritised. Vukovic was awarded £40,000 to purchase a thermal camera and a drone to carry out research into capturing energy leaks in buildings. The results were used in the proposal for the Horizon 2020 eDREAM project (see section 3), with Vukovic now leading a work package on integrating tools developed within the project for demand response energy services.

Research students

Our doctoral training programme has more than doubled in the period. Since August 2014, we have registered 125 postgraduate students and completed 10.4 awards per year, compared with 5.5 in REF 2014.

We have invested £3.3m, from both internal and external funds, in 44 studentships over the period. This has supported: 14 institutional studentships (£914,000); seven university alliance studentships (£588,000); 13 graduate tutor studentships (£1.3m); seven fees-only studentships (£256,000); and three EU COFUND projects (£189,000).

Research centre postgraduate project opportunities are advertised annually via the university web pages and findaphd.com, and are promoted via postgraduate open days and university/school and researchers' social media. We work closely with the student recruitment and marketing (SRM) team to ensure our recruitment process is accessible to all protected groups and that our advert outlines our commitment to equality, diversity inclusion. FAQs (including those related to access) are posted on the postgraduate student web pages and student enquiries are fielded to potential supervisors via the postgraduate tutors who oversee postgraduate supervision. Specialised support for international applicants requiring student visas is overseen by staff within the admissions and compliance functions of international admissions located within SRM.

We co-manage the University Alliance (UA) doctoral training alliance (DTA) Energy programme, which involves 14 universities and is focused on producing doctoral graduates to address global energy challenges. DTA Energy provided training for seven PhD students between 2016 and 2020, including: seminars on topic-specific training; a mandatory two-day induction for networking; an annual two to three day summer school and conference; elective training events that bring the DTA programme cohort together from participating institutions.

We are part of a €13m Horizon 2020 COFUND funded DTA3 project (an extension to the UA DTA programme, grant number 801604), which brings together a consortium of 12 universities in England and Wales. The aim of DTA3 is to develop researchers to be internationally connected with the interdisciplinary and industry skills required for employment in European and UK priority challenge areas; it hosts an autumn induction and an annual summer school and in 2019 initiated an international conference on Energy and Sustainable Futures (co-chaired by Vukovic). Selected papers are published in special issues of the International Journal of Design Engineering and Frontiers in Engineering Management, 2019. Three students have been recruited through DTA3, and we expect to appoint four more by 2022.

Directors of PhD study (DoS) and postgraduate research tutors run a research diagnostic for each PhD student in their first three months to identify needs and proposals are put forward for to improve gaps in students' knowledge and understanding. Our induction and progression processes include an individual training needs analysis and local training is delivered via a research centre programme to support research practice.

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English language support for postgraduate research students and researchers is provided, as required, by the university's English Language Centre.

In addition, the research centres provide students with access to a bench fees budget of £2,500 per annum for equipment, use of external research facilities and consumables.

Meetings between the student and the supervisory team are recorded via the university's e-Vision system to track supervisory meetings and monitor postgraduate progression. Monthly reports from supervisors are monitored by the school to ensure progress-related issues are addressed as early as possible. Annual progress is monitored through an annual review, which is a formal interim assessment point.

The unit hosts a monthly forum for PhD students to rehearse presentations and communicate their research. It provides an opportunity for students to exchange ideas, share experiences and find out about development opportunities. A postgraduate lounge is located centrally on campus to strengthen the postgraduate community and enable students to meet informally, across disciplines. Our research students present their work at our annual research conference attended by industry representatives and international visiting researchers. Feedback on technical content and presentation style is given through a panel of experts.

Following the Covid-19 lockdown in March 2020 all postgraduate students were issued with a blanket three-month extension with the option of requesting a further three-month extension where they have been unable to continue with their research. The university met the additional fee and stipend costs where external funding was unavailable.

Equality and diversity

The university's Equal Opportunities Policy guides all recruitment, promotion, and research activities. Our staff complete the university's mandatory training on equality and diversity within a three-year period, and new staff (monitored by the research centre leads) are encouraged to complete this within their first year. Our unit is committed to equality and diversity and staff are active in supporting a number of university, school and unit initiatives. For example, Dawood N and Thompson are both Athena Swan champions working to deliver the university's Athena Swan Bronze action plan to address the underrepresentation of female staff in the unit and supporting preparations for an Athena Swan Silver application in 2021. Jayne (2020) is leading the establishment of the Teesside Women in Engineering Group to promote female staff in engineering and support their career development.

Our equality impact assessment (EIA) has shown that women are underrepresented in the unit for both eligible and submitted staff. Of 151 eligible staff, 111 are male (73.5 per cent) and 40 are female (26.5 per cent). Of the 79 staff with SRfR, 59 are male (75 per cent) and 20 are female (25 per cent).

Black and Minority Ethnic (BAME) staff are also underrepresented in the unit's eligible staff pool, however this pattern is reversed for those staff with SRfR who are part of this submission. Of the 151 eligible FTE staff, 87 are white (58 per cent) and 61 are BAME (40 per cent). Of the 78.6 FTE staff with SRfR, 31 are white (39 per cent) and 47 BAME (59 per cent).

The number of staff who disclosed a disability, and low disclosure rates against sexual orientation, limit the extent to which conclusions could be drawn within the EIA. The relatively low level of disclosure is of concern to the unit and we will continue to work with the university's active LGBTQ+ focus group. A number of events and campaigns to increase visibility and awareness are held by the university. This has included a video, a coming-out story, which university staff and students contributed to.

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A number of improvements to equal opportunities at university and unit level have been achieved during the period. As a result of the current Athena Swan action plans, the university has changed its recruitment to include: using advertising language that is proven, preferred, modern language for attracting a broader range of applicants; identifying its family friendly policies, including flexible working, job share, sabbaticals and secondments; and encouraging the promotion of vacancies through social media, which has been supported locally for both staff vacancies and postgraduate studentship opportunities.

To guard against unconscious bias, and in line with the DORA action plan, the university's recruitment and promotions guidance informs applicants that bibliometric measures such as the H-index or journal impact factor (JIF) will not be considered. Instead, it asks candidates to identify up to four outputs that they would be prepared to talk about at interview in terms of their significance and wider impact. These practices have been implemented at both school and unit level. In line with our university code of practice, both external and internal reviewers evaluating the quality of research outputs for this submission were advised not to base their judgement on JIFs.

Since 2018, three years of Athena Swan data on gender (at university and school level) have been analysed and presented to the Athena Swan champions as part of an annual Athena Swan review. These data include information on gender in relation to recruitment, shortlisting, promotions and training opportunities. The champions consider local and university-wide changes that can be implemented to make a positive difference to the diversity and equality of opportunity at unit, school and university level. As a result, in 2020, Thompson supported a revision to the promotions criteria and protocols and the unit and schools have implemented recommendations for staff returning from maternity such as the maternity passport, carer policy and carer passport.

Since 2018, we have been part of an EPSRC-funded consortium of nine universities and six industrial partners, Northern Power: Making Engineering And Physical Sciences Research A Domain For All In The North Of England, EP/S012206/1, to shape an inclusive culture in the engineering and physical sciences community that supports and sustains greater equality for all, including traditionally under-represented groups (such as women, disabled people, LGBT+, and BAME researchers). The aim is to transform cultures to enable a wider and more diverse pool of talented individuals to progress within the community, which will ultimately produce better science to address complex and important global challenges. Tools, webinars, training materials and an inclusion matters newsletter have been developed and shared across the unit and staff have been invited to join the network's reciprocal mentoring scheme.

To further support equality, diversity and inclusion, and the region, the university (led by Jayne) signed up to Tomorrow's Engineer's Code which pledges to support young people to participate in impactful engineering-inspiration activities regardless of characteristics, socio-economic background, prior attainment or location.

Two training sessions were delivered by Advance HE for staff involved in the preparation of the REF2021 submissions (for example the associate dean for research and innovation, the UoA 12 committee, impact champions and impact case study authors) on EDI issues in relation to the university's code of practice protocols for identifying staff with SRfR, determining independence and the selection of outputs.

Staff with long-term illness, or caring responsibilities, are supported by their school's flexible working arrangements and carer's passport scheme which supports discussions between staff and their managers about bespoke support for their circumstances.

3. Income, infrastructure, and facilities

Income

Our annual RGCI increased by 57 per cent over the period, from £0.8m in 2014 to £1.3m in 2020. Our aim to grow research grant and contract income has been focused on: developing a portfolio of projects in key areas by engaging in large consortia funded by the European Commission; providing early and mid-career researchers with the opportunity to participate in these projects; and developing industry partnerships through collaborative research, including KTPs.

Forty per cent of our income (£3.6m) was generated through EU research funding programmes Framework Programme 7 (FP7) and Horizon 2020 (H2020). We have used these projects to develop tools and technologies in key areas within our research centres.

This includes a portfolio of projects with a total value to the unit of €3.8m based on ICT for energy efficiency in the built environment. These projects have supported the development, refinement and demonstration of prediction/forecasting tools, optimisation models, visualisation technologies, and integration platforms. These have been incorporated into energy management and decision support tools, with key contributions from the unit as follows:

- SEMANCO (Semantic Tools for Carbon Reduction in Urban Planning), Grant Agreement (GA) 287534, 2011-14. €2.7m for nine partners, including €0.5m for the unit.
Key contributions: identifying user requirements to inform the selection, design, integration, and implementation of energy simulation and trade-off visualisation tools. The project developed methodologies for constructing 3D models from images taken by drones. These have been used and developed further in the eDREAM project (see below).
- IDEAS (Intelligent Neighbourhood Energy Allocation and Supervision), GA 600071, 2012-15. €2.7m for 10 partners, including €0.5m for the unit as project coordinator.
Key contributions: defining and operationalising the concept of energy positivity in neighbourhoods; developing specifications for an ICT-based neighbourhood energy management tool; prototype development of the energy management system. The tools have been refined and used for the DR-BOB project below as optimisation energy tools for energy demand response.
- DR-BOB (Demand Response in Blocks of Buildings), GA 696114, 2016-19. €4.3m for 10 partners including €0.9m for the unit as project coordinator.
Key contributions: development of the local optimisation and decision support system for demand response, and integration with a cloud-based platform; developing implementation strategies for the demonstration sites; running the UK demonstration site; analysis of results. The tools have been customised and are currently been adopted in eDREAM (see below).
- InteGRIDy (Integrated Smart GRID Cross-Functional Solutions for Optimized Synergetic Energy Distribution, Utilization Storage Technologies), GA 731268, 2017-21. €12.3m for 32 partners, including €0.6m for the unit.
Key contributions: leading the work packages and tasks relating to life cycle assessment and cost/benefit analysis of implementing energy efficient solutions and an integrated portal for ten pilot sites across the EU. This uses methods and processes developed in IDEAS above.
- eDREAM (enabling new Demand Response Advanced, Market oriented and Secure technologies, solutions and business models), GA 774478, 2018-21. €3.8m for 10 partners including €0.5m for the unit.
Key contributions: energy consumption baseline modelling; work package lead for

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integrating visualisation and optimisation tools for DR services, which includes further development of the visualisation tools from the SEMANCO project.

- REACT (Renewable Energy for self-sustAinable island CommuniTies), GA 824395, 2019-22. €9m for 23 partners, including €0.6m for the unit.
Key contributions: leading work package on the user context and socio-economic analysis; infrastructure integration; supporting development of energy prediction and optimization tools, including further development of the optimisation tools from IDEAS and DR-BOB.
- SMEmPower Efficiency (A holistic framework for Empowering SME's capacity to increase their energy efficiency), GA 847132, 2019-22. €2m for 11 partners, including €0.2m for the unit. Key contributions: development of energy analytics tools; technical support and UK-wide promotion of project opportunities. This project tackles energy efficiency in SME manufacturing companies.

This work has been led by Dawood N, Crosbie and Short, and opportunities to gain experience from the projects as co-investigators have been provided to Pillai, Shadman-Pajouh and Vukovic. Dawood H, and Rodriguez were employed as research associates on these projects before moving into lecturer roles during the REF period.

The project portfolio led by Ali and Islam is based on the use of research funding to support low technology readiness level (TRL) projects, accessing translational funding for work at a higher TRL, and moving from national to international funding to extend the impact and reach of the research.

TRL 3/4 research on cavity enhanced absorption (CEA) detection was supported via FP7 project CE-microArray (Cavity Enhanced Microarray as an Ultra-sensitive Tool to Aid Sepsis Diagnosis, GA 606618, €1.1m including €0.4m to the unit as coordinator) and H2020 project GateOne (Innovation Service for European Smartization by SMEs, GA 644856, €5.4m for 10 partners, including €0.4m for the unit. The unit's IP on CEA detection in liquids (US 8,325,342 B2) was exclusively licensed to university spin-out company Anasyst, which subsequently led a translational research project (TRL 5/7) from the National Institute for Health Research (NIHR) Invention for Innovation (i4i) programme (Grant reference II-BP-0817-10012) to develop a point-of-care diagnostic for sepsis using CEA detection. Anasyst is in the process of seeking investment funding to commercialise the system.

Overall, 47 per cent (£4.3m) of our funding over the period came from UK industry and government to support collaborative research including Innovate UK-funded collaborative R&D projects and KTPs. Over the period we have delivered 27 KTPs and two (ERDF-funded) short KTPs with a number of companies including: Ryder Architecture, Colour Urban Design, Niven Architects, Hodgson Sayers, Sotech, Applied Integration, Datum 360, Unasys, Charles Clinkard Teleware, Lexonic, Modus and VisualSoft.

Innovate UK projects have focused on three areas: Food manufacture and processing techniques (Increasing Efficiency in Fried Food Production: Oil Take-Up, Energy Use and Shelf-Life, grant 23279-161174; MCAP2 - Measurement and Control of Acrylamide in Production Processes, grant 94447-562636); Advanced materials for high performance in extreme environments (Advanced Electrical Machines Technologies for Aircraft, Aemta, grant 36590-262175 and High Temperature Materials for Electrical Machines HiVEM, grant 101487/ETC00220) and healthcare technologies combining expertise from the HIC and the Centre for Digital Innovation (Intelliscan and QuickFit projects).

Senior appointments made during the cycle (three professors and four readers) will deliver additional income growth beyond 2021 and support ECRs to develop their first awards. Our

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research strategy (2020-25) commits to invest in 14 senior appointments and to attract research fellowships with a view to increasing the financial sustainability of the unit.

This along with our investment in facilities (£12m Net Zero Industry Innovation Centre, £2m ERDF-funded Industrial Digitalisation Technology Centre and £13m Digital Life centre) and TWI innovation centres will support the generation of future collaborative research income.

Infrastructure and facilities

Engineering researchers can access a range of facilities within the university, with much of this equipment base having been developed through university investment in this REF census period. This is due to be substantially further enhanced through the investment plans for the next five years, including a £12m Net Zero Innovation Centre opening 2022 and providing specialist research capability in: hydrogen and other low C fuels; energy conversion and storage, intelligent energy and industrial systems; the circular economy, advanced recycling and resource recovery technologies; digital modelling and simulation; thermal technologies. A further £13m investment is planned in our Digital Life Centre which will include significant infrastructure to support our research in digital and computing technologies.

In 2016, we invested £3.1m in our main engineering building, followed by an additional £2.6m upgrade to further enhance our laboratory facilities with equipment to support chemical engineering and materials engineering and manufacturing activities, process control, manufacturing and food-processing.

Our equipment base for manufacturing research now includes: polymer processing; 3D printing; robotic production and assembly; anodisation and electroplating; lean manufacturing cell, robotic production and assembly; a specialist system for the production of electrical insulation on wire (at the kilometre scale) and wound components; supervisory control and data acquisition (SCADA) control laboratory; and various biomanufacturing facilities including reactor column, sterilise-in-place (SIP) bioreactor and retort pasteurisation, plus water treatment.

We have a range of electrical test facilities from picoamp up to the kilovolt range, a range of mechanical testing facilities for static and dynamic loads from the micro scale up to a heavy structural testing laboratory, as well geotechnical characterisation, testing and measurement. Other Geotechnical research facilities support experimental work related to the characterisation of porous media (such as rocks) with particular application in carbon capture and storage.

In addition, between 2018 and 2020, approximately £80,000 of seed-corn funding has been invested in a testing facility for development of novel techniques for Li-Ion battery state-of-health and state-of-charge estimation. To date this has yielded six journal articles, has supported the work of three PhD research students and helped to support two funding bids.

These activities are supported by a full range of modelling software for design, mechanical and finite element analysis (NX I-DEAS, SolidWorks) and for the analysis of buildings and architecture (Autodesk REVIT, Uc/Win Road, Bentley), and a general purpose workshop with dedicated technical staff, which is extensively used to support research activities. These facilities have been used for KTPs and research projects on the development of BIM funded by the Qatar National Research Fund (Development and Application of a Novel and Integrated Performance Driven Approach for Assessing, Benchmarking and Improving BIM Competency of Qatar's Construction Industry Practitioners, NPRP 9-124-2-062).

Other specialist digital research facilities include networked computing studios for programming, cybersecurity, web and application development. Our games, animation and visual effects studios provide research facilities to support virtual reality and augmented reality, animation and digital

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compositing, games and application development alongside a networked render farm, which allows for optimisation of digital assets.

We have access to a £5m suite of chemical analysis facilities including: liquid chromatography with ion trap mass spectrometric detection; inductively coupled plasma mass spectrometry and atomic absorption spectrometry for elemental analysis in a range of matrices; a 400 MHz nuclear magnetic resonance facility, X-ray fluorescence and X-ray diffraction; EDX equipped scanning electron microscopy; a range of gas chromatography-mass spectrometry and high performance liquid chromatographic capabilities; and thermal analysis.

Other analytical facilities include: microscopic infra-red and Raman spectroscopies for micro-scale chemical analysis; physical and chemical surface measurement techniques including surface energy and atomic force microscopy; and a dedicated CATLAB system for the real time measurement of catalyst chemistry using Mass Spectroscopy, Brunauer-Emmett-Teller (BET) analysis.

In 2019, the university opened the National Horizons Centre, a £22m purpose-built research centre with extensive materials-characterisation facilities further enhancing our research infrastructure and facilities including: a wide range of ultra-performance liquid chromatography and gas chromatography capability; confocal microscopy; confocal Raman imaging; mass spectral imaging (both MALDI and DESI); and integrated/Fourier transform infrared/near infrared/Raman spectroscopy. Islam leads the materials characterisation aspects of research conducted at this facility.

Our formal research partnerships through our innovation centres (with TWI) and regional health trusts have also allowed us to access and develop a range of specialist facilities to support our research on biomedical device development through the HIC. These include a joint facility for micro structuring and metrology of miniaturised devices developed with TWI in Middlesbrough, which is located close to the university. Our equipment at this site includes: a scanning electron microscope (SEM) with focused ion beam (FIB) (FEI Quanta 200 3Di); inkjet 3D printing (Stratsys, Objet 350 Connex 3); and micro-milling (Datron M9 mill). TWI's equipment includes: an atomic force microscope (Bruker, Innova); white light interferometer (Bruker, Contour GT-K); and tribometer (Bruker, UMT Tribolab).

This joint equipment set has been used for the fabrication and characterisation of microfluidic devices, novel pressure and shear sensors and instrument prototypes for various projects. This includes the GateOne, SepsisPoC and QuickFit projects listed above, and the Horizon 2020 SocketSense project (Advanced Sensor-based Design and Development of Wearable Prosthetic Socket for Amputees, GA 825429). We also benefit from the additional expertise available within TWI and the development of links with TWI's industrial partners and clients, while our research partnerships with two large NHS trusts in South Tees and North Tees provide us with access to clinical facilities and anonymised data, for example to support the Intelliscan project.

In addition to these strategic research partnerships, a number of staff are involved and supported in active collaborations with other institutions which provide access to specialist facilities not available in-house, for example Islam (Oxford and Cambridge), Dawood N (Miyagi, Japan, and Gyeongsang National University, South Korea), Ali (VTT, Finland), and Sargent (RMIT, Australia).

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

Support for collaboration

Our approach to collaborations and partnerships is reflected in our innovation centres with TWI, industrial projects funded by Innovate UK, the EU and other international funders (detailed in section 3 and below.) Staff are supported to develop collaborations including internationally

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through: targeted advice in their PDPR and ongoing support from their mentor; the development of personalised bidding plans; the allocation of pump-priming funds; support for conference and networking event attendance and collaborative visits.

Horizon scanning for collaborative funding opportunities is supported by Research and Innovation Services and the Department for Academic Enterprise. These departments provide weekly bulletins about research opportunities, support to identify and develop links with targeted industry partners, bid development and post-award support.

The outcomes and impacts of collaborative projects are used to deepen links with existing partners and build relationships with new stakeholders. They are also used in teaching, including the development of final-year undergraduate and MSc projects, and in the university's students as researchers scheme, which provides paid positions for students to work on a live staff research project. Project outcomes and initiatives such as the establishment of the innovation centres with TWI are shared at research centre and theme meetings so that links to other research areas can be identified and opportunities for collaboration explored. The innovation centres hold quarterly meetings with TWI to review funding roadmaps and horizon scanning exercises.

Staff are supported to hold conferences on-site, with examples including: the European Steel Environment and Energy Congress (ESEC) in 2014; Adapting buildings for future climate change (ADAPTBUILD) in 2017, a joint event with the University Alliance DTA and the Australian Technology Network of Universities (ATN); and the Analysis of and Analysis on Networks workshop with the support of the London Mathematical Society in 2019.

Staff are also supported to make and host research visits, including: Pak, who visited Brazil, including the Brazilian Synchrotron Light Laboratory and the universities of Parana and Sao Paolo, leading to the development of her GCRF QR project detailed in section 1; Pang, who visited the Polymer Materials Institute, Sichuan University and the Biomaterials Department, Southwest Jiaotong University, China to present his work on high temperature insulation and electrode materials; and Sargent who visited North China University of Water Resources and Electric Power to discuss alkali activated cements in soil stabilisation and geopolymers.

The unit also encourages staff to host visits, with examples over the period including: researchers from: the All India Institute of Medical Sciences, India (Ali); National University of Singapore (Qin); RMIT University, Australia (Sargent); and Beihua University, Najing Institute of Technology, Anyang Institute of Technology, and Wuhan Polytechnic University, China (Xu).

Senior staff (Ali, Dawood N) have provided opportunities throughout the period for others to benefit from their networks by participating in funded projects (Crosbie, Islam, Short, Vukovic), and these staff are now providing similar opportunities in turn within the projects they lead (to Dawood H, Pillai, Rodriguez, Shadman-Pajouh).

Collaborative and interdisciplinary projects

Our research is aligned to regional (Tees Valley Combined Authority), national (Industrial Strategy, EPSRC) and international (H2020/Horizon Europe, UN sustainable development goals) priorities, allowing us to respond to emerging initiatives using interdisciplinary approaches.

We have an established track-record of providing a combination of technical and social expertise to projects, both within the unit and in collaboration with other research centres across the university and external partners. Key themes of this work include user engagement, user needs and experience, technology acceptance and implementation and ethical issues as seen in the following examples:

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- The REACT project combines Short and Pillai's work on sustainable technologies and control engineering with Crosbie and Shadman-Pajouh's expertise in user experience evaluation to demonstrate the potential of renewable energy systems to bring economic and social benefits.
- The What is in a Meter project aims to extend the technical aspects of energy metering into the broader aspects of impact on access to water and electricity. This combines expertise in the build environment and ICT (Crosbie), modelling and simulation of energy systems (Pillai), and public health, (Newbury-Birch, centre for social innovation).
- The SMEmPower Efficiency project combines technological expertise in energy informatics (Dawood N) with business models (Dawood H) and processes to create innovation (Rodriguez, Patacas)
- The PYROCHAR project (PYROlysis Based Process to Convert Small WWTP Sewage Sludge into Useful bioCHAR, FP7 research for SMEs, 603394) combined Ennis and Olea's research on heterogeneous catalytic technology and pyrolysis with external expertise in European and national wastewater regulations.
- Exploring approaches to enhance the safety and ethical implications of the global race to develop artificial intelligence through a prestigious international collaborative Future of Life Institute project (Han)
- The development of 3D Structured Light imaging techniques, technical and associated ethical standards and for Forensic Medicine, Criminal Investigation, Forensic Anthropology and Archaeology (Thompson) – also submitted as an impact case study. [ICS N6]

Our track record of collaborative projects includes work within our research centres. At the Centre for Sustainable Engineering we have delivered the FP7 and H2020 projects on ICT for energy efficiency outlined in section 3, and the following Newton Fund projects developed collaboratively with international partners:

- Micro-Bubble Aeration System for Aquaculture Under Energy, Water Quality and Biofloc Circulation Constraints In Malaysia (EPSRC/Newton Fund, EP/P018211/1) (Hamad with University of Malaya)
- Introducing New Techniques to Manage Challenging Oil Reservoirs (NRCP1516/4/46, Rezaei Gomari with Centro Universitário da FEI, Brazil)
- Development of X-ray Tomographic Techniques to Investigation of Fluid Transport in Porous Rocks (NRCP1516/1/159, Pak with Federal University of Santa Catarina, Brazil)
- Exploring Adsorption Efficacy of Sustainable Nanoporous Carbons Produced from Agricultural By-Products (NRCP1516/1/83, Yin with Hanoi National University of Education, Vietnam)
- Development of Sustainable Nanocellulose-Based Sorbents for Industrial Wastewater Treatment (264232317, Yin/Alí with Centro de Investigación en Materiales Avanzados, S.C. (CIMA), Mexico).

Other collaborations with a range of international partners including: in Europe with the Technical University of Denmark (Suleman), Universitat de les Illes Balears in Mallorca (Short), University of Cantabria in Spain (Baldini), University of Turin in Italy (Pak), Universities of Warsaw and Wrocław in Poland (Baldini); In Asia-Pacific with the Chinese University of Hong Kong (Li E), the Indian Institute of Technology Bombay (Pillai), Institute of Microelectronics of the Chinese Academy of Sciences (Li J), Monash University Malaysia (Subramonian), Nanyang Technological University, Singapore, Universitas Multimedia Nusantara, Indonesia (Al Kafri), Universiti Teknologi PETRONAS, Malaysia (Suleman, Syed) VIT Chennai, India (Short), University of New South

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Wales (Baldini, Syed); University of Sydney and University of Wollongong, (Li E); and in North America with East Carolina University (Sargent), Ontario Tech University (Patel), University of Cincinnati (Li E), University of New Mexico and University of South Florida (Baldini), University of Western Ontario (Taylor).

Some of our major research collaborations at the Centre for Digital Innovation in this period include:

- The FP7, H2020, FLI, Innovate UK and NIHR projects detailed in section 3 on diagnostic devices and artificial intelligence
- An AI-enabled Digital Diagnosis, Empowerment and Participatory Platform for HFMD Surveillance (British Council Newton Fund, 527643161, Razzaque with King Mongkut's University of Technology Thonburi, Thailand)
- The Improvement of TV Show and Film Recommendation Through Artificial Intelligence and Machine Learning (Innovate UK project, 104578, Angione/Zeng with industry partners)

Other international collaborations have been carried out with European partners including: Fraunhofer Institute for Photonic Microsystems, Germany; CEA-Leti & LAAS CNRS, France; VTT, Finland; KTH Royal Institute of Technology, Sweden; CSEM, Switzerland; IKERLAN, Spain (all Ali); EM Normandie Business School, France (Chang); Universidade Nova de Lisboa, Free University of Brussels (Han); National Research Council of Italy (Occhipinti). In Asia we have worked with the Chinese Academy of Science, Nanjing University, Shenzhen University, East China Normal University, Nanyang Technological University and the National University of Singapore (Qin); and in North America partners include PwC Labs, California and Quinnipiac University USA (Chang).

Impact and engagement

Beyond our impact case studies, our research has enabled commercial, environmental and social impact, and our staff are supported by their mentors to embed impact into their bidding plans and project development.

Our focus on KTPs allows us to directly apply our research outcomes working with industry partners. Over the period, we have delivered KTPs focusing on manufacturing, building and fabrication, architecture, energy, advanced materials, automated systems, instrumentation for process control, biotechnology and pharmaceuticals, digital forensics, software development, and hazard detection and protection including for the oil and gas and petrochemical industries. These areas reflect the range of strengths within our research centres.

We also engage with H2020 and ERDF projects to develop impact from our research. The GateOne H2020 (Ali) project provided 'innovation as a service' to accelerate smart systems adoption by European SMEs by facilitating access to advanced technologies. We supported the application of additive manufacturing technologies by local SMEs via the ERDF Innovate Tees Valley project (022NE1420) and are currently a partner with TWI in the ERDF SME Innovation Accelerator (34R20P041338). This programme aims to support innovation in new products and processes amongst SMEs in the Tees Valley including by providing product prototyping support.

We participate in a regional ERDF initiative, Intensive Industrial Innovation Project Tees Valley (34R17P02148) and Intensive Industrial Innovation Project North East (25R17P01847), to deliver collaborative PhD programmes with industry partners. This provides unit members with an opportunity to work directly with industry, with relationships brokered by the university. Six students have been recruited across a range of projects, including: the development of novel optical measurement tools for the measurement of vital signs in clinical practice; strategic recycling and

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valorisation of waste plastics to support the circular economy; and the metabolic modelling of biofilms

As part of the IDHIC and our commitment to the Net Zero Industry Innovation Centre, we have used ERDF funds to develop a hydrogen demonstrator lab (Tees Valley Hydrogen Innovation Project, 34R17P02147). Led by Krishnan and Russell, the aim is to support SMEs in the Tees Valley to access academic expertise and engage with the opportunities afforded by the hydrogen economy, based on purifying the hydrogen produced by industry for domestic use. Although affected by the Covid-19 pandemic, the project has supported three companies to date and is due to run until 2023.

We work in partnership with the Universities of York and Hull on the Research England Connecting Capability Fund THYME project (Teesside, Hull and York mobilising bioeconomy knowledge exchange), which supports collaborative research with industry partners. Our activities include: the development of a scaled-down automated micro-bioreactor system with integrated downstream analytics for bioprocessing (Ali/ Montague with Unilever), which demonstrates the miniaturised microbioreactor developed within GateOne; an investigation of the repurposing of process scale assets to demonstrate anaerobic digestion innovations (Montague with Yorkshire Water); the application of a novel triglyceride oil from Alexanders seed in food products (He with Naturiol Bangor); and the fabrication of a microbubble bioreactor to facilitate rapid growth of the extremophile *Galdieria* to convert the combination of waste bio-glycerol and waste jewellery acid to high value phycocyanin (Angione with Perlemax).

We benefit from strong links to major companies based in the local area, such as Fujifilm Diosynth Biotechnologies, the Centre for Process Innovation and the South Tees Development Corporation (STDC), which manages Teesworks, the largest industrial zone in Europe comprising a brownfield site on the banks of the river Tees. We have collaborated with the Centre for Process Innovation and Fujifilm on the application of constraint-based modelling techniques for multi-omic characterisation of cell metabolism (Angione), with Fujifilm on a collaborative PhD on a microfluidic tool for cell line production (Ali) and with STDC on ground remediation (Sargent).

Contribution to the discipline

Unit members are active on grant committees, including full membership of the EPSRC peer review college (Dawood N, Han, Qin), and membership of the UKRI future leaders fellowships peer review college (Ali, Qin) and the college of experts for the global effort on Covid-19 health research call (Ali). Additional grant committee membership includes: the UK Doctoral Researcher Awards, Scientific Executive Committee (Angione); the Government of Ireland Postgraduate Scholarship Program STEM Outer Board and Postdoctoral Fellowship Scholarship Scheme STEM Outer Board (Baldini); and the Research Council of Oman (Suleman).

Unit members are also grant reviewers for funders including: BEIS (Vukovic); British Council (Al-Greer); Dutch Research Council NWO (Islam); European Commission (Baldini, Hossein, Vukovic); Innovate UK (Ali, Rahimian); Innovation Fund Denmark (Vukovic); Irish Research Council (Baldini) Leverhulme Trust (Baldini, Rahimian); Natural Sciences and Engineering Research Council of Canada (Li); Portuguese Foundation for Science and Technology (Vukovic); Research Foundation Flanders (Pak); Swiss National Science Foundation (Islam); and UKRI (Angione, Baldini, Hamad, Hossain, Pak, Rahimian, Short, Vukovic).

Staff are also members of a range of professional bodies and societies including: Association for Computing Machinery (ACM); Institute of Chemical Engineers; Institute of Electrical and Electronics Engineers (IEEE); Institution of Civil Engineers; Institution of Engineering and Technology (IET); Institution of Mechanical Engineers (IMechE); and the Royal Society of Chemistry.

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Staff hold fellowships at: Chartered Society of Forensic Sciences (Thompson); Geological Society of London (Sargent); Institute of Biomedical Science (Taylor); Royal Anthropological Institute (Collings, Thompson); Royal Society of Biology (Thompson); Royal Society of Chemistry (Ali); and an honorary fellowship of the Faculty of Forensic & Legal Medicine (Thompson).

Jayne is president elect of the International Neural Network Society (INNS).

Prizes awarded to unit members during the period include: the best paper award (mechatronics track) at IEEE International Conference on Robotics and Automation Sciences 2020 (Short); the MCED award for innovative contributions to ecological modelling 2016 (Angione); the Asian Pacific Association for Computational Mechanics award for young investigators in computational mechanics at the Asian Pacific Congress on Computational Mechanics 2019 (Li E); the international computational method young investigator award at the 10th International Conference on Computational Methods 2019 (Li E); and the best paper award at Proceedings of the 4th World Congress on Momentum, Heat and Mass Transfer 2019 (Patel).

Examples of editorial responsibilities during the period include:

- Editor-in-chief roles: Journal of Forensic and Legal Medicine (Thompson); Micro and Nanosystems (Ali); Science and Justice (Thompson); Smart and Sustainable Built Environment (Rahimian).
- Editor roles: Future Generation Computer Systems (Chag); Information Fusion (Chang); International Journal of 3D Printing Technologies and Digital Industry (Hughes); International Journal of Architectural Research: ArchNet-IJAR (Rahimian).
- Associate editor roles: BMC Bioinformatics (Angione); Energies (Short); IEEE Access (Qin); IEEE Transactions on Industrial Informatics (Chang); IEEE Transactions on Neural Networks and Learning Systems (Jayne); IET Power Electronics (Al-Greer); International Journal of Intelligent Automation and Soft Computing (Xu); International Journal of Computational Methods (Li E); Journal of Medical Imaging and Health Informatics (Li E); Open Access Journal of Science (Syed); PeerJ Computer Science (Qin); Smart and Sustainable Built Environment (Rodriguez).
- Editorial board membership: BioMed Research International (Angione); Construction Innovation, Information, Process, Management (Rahimian); Forensic Anthropology (Thompson); Frontiers in Robotics and AI (Han); Human Remains and Violence (Thompson); IoT Journal (MDPI) (Razzaque); International Journal of Distributed Sensor Networks (Razzaque); International Journal of Novel Ideas: Mathematics (Li E); International Journal of Speleology (Baldini); PLOS One (Han); Journal of Forensic Sciences (Thompson); Soil Forensics (Taylor); Visualization in Engineering (Rahimian).

Dawood N founded and continues to lead the annual International Conference on Construction Applications of Virtual Reality (CONVR). This has been held in 15 countries since 2000, and brings together a community of researchers from a range of architecture, civil engineering and construction disciplines to focus on the application of virtual reality and augmented reality

In addition, numerous staff have been involved as members of conference organising committees both within the UK and internationally including for: the Association for The Advancement of Artificial Intelligence; the Chartered Institution of Building Services Engineers; the IEEE; the International Council for Research and Innovation in Building and Construction; and the International Federation of Automatic Control.

Unit staff have undertaken a range of conference chair and organising committee memberships including: Jayne as general chair of the Engineering Applications Neural Networks Conference (EANN) in 2016 and 2019 and as program chair of the International Joint Neural Network

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Conference (IJCNN) in 2017; Chang as chair of the Enterprise Security (ES 2014, 2015 & 2016), Emerging Software as a Service and Analytics (ESaaS 2014 & 2015) events and the International Conferences on Internet of Things, Big Data and Security (IoTBDs) in 2016 and 2020, and Complexity, Future Information Systems and Risk (COMPLEXITY).