Institution: Nottingham Trent University (NTU)

Unit of Assessment: B12 – Engineering

1. Unit context and structure, research and impact strategy

Solving modern engineering problems requires an interdisciplinary approach. At Nottingham Trent University (NTU) Engineering, we embed this principle in the way we do research, by bringing together complementary strands of multidisciplinary research in the applied sciences. Reflecting our interpretation of NTU's institutional strategy, 'Creating the University of the Future', our vision is: 'To create creative engineering and engineers that will shape the future world.'

Building on the strengths documented in RAEs 2001/2008 and REF2014, we have enhanced our established world-class research in the areas of imaging and materials and expanded our research focus to include smart technologies and medical technologies. Since 2014, we have undergone a period of growth, with significant investment in staff recruitment and in facilities:

- we have added over 20 new academic positions across the Unit of Assessment (UoA), more than trebling its size;
- we have matched this with over £50m capital investment in three state of the art new buildings and corresponding equipment;
- this steep upward trajectory is reflected in our research income capture which delivered £1.7m/year of spend in REF2021 with a rising trend of £4.3m of new awards in 2020; and
- in our ability to attract high-profile award-winning scholars and in recognition such as the Queen's Anniversary Prize.

1.1 Engineering Research Unit Structure

NTU maintains complementary structures for the development of teaching (by department) and research (by research centre). The B12 submission is structured around the **Imaging, Materials and Engineering Centre (IMEC)** and includes staff from the departments of Engineering, Physics, Maths, Chemistry and Computer Science, all housed within the School of Science and Technology. The School Research Management Team is led by the Associate Dean for Research (ADR), a role created for all academic schools at NTU since 2014 (see REF5a). The Team also comprises the four School Research Centre Directors and Postgraduate Research Tutor. The ADR is a member of the University Leadership Team and the Academic Research Leadership Team and collaborates closely with the Deputy Vice-Chancellor - Research and Enterprise.

As a central point, IMEC coordinates activities supporting the development of a vibrant research community and an inclusive research culture. These include weekly seminar series, research/impact leave, and support for early career researchers (ECRs) and postgraduate researchers (PGRs). The Centre's interests are balanced through an advisory group consisting of the relevant heads of department, departmental research coordinators and selected professors. The advisory group manages the distribution of resources available to IMEC and provides leadership related to the implementation of our research strategy, along with targeted support and mentoring.

This interdisciplinary centre is then comprised of four research groups which represent critical masses of similar interests, and which aim to nurture highly impactful research. Expertise includes the different stages of impact (e.g. applied research, industry involvement and spin-out companies) working within each group.

- **Imaging** (in REF2014, Imaging and Sensing) encompasses cutting-edge non-invasive imaging techniques and their applications. Examples include: the Imaging Science lab, headed by Evans, whose pioneering X-ray technology can rapidly scan for the presence of illicit materials, with impact in airport security via spinout HALO X-ray (and cited in NTU's Queen's Anniversary Prize, 2015); and Liang's ISAAC (Imaging and Sensing for

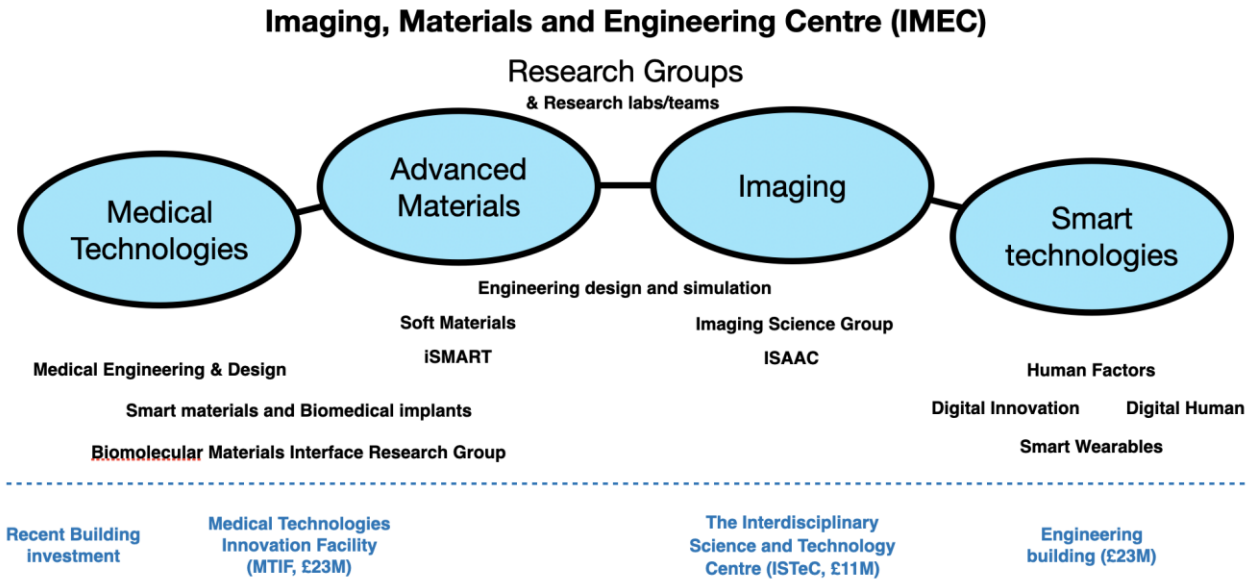
Archaeology, Art History and Conservation) lab, whose suite of 3D spectral imaging, remote sensing and sub-surface imaging links to institutions including the British Museum, the National Gallery, the Smithsonian Institute and the Louvre.

- **Advanced Materials** (in REF2014, Bio-materials and Materials Engineering) describes our approach to the design of functional materials from the bottom up. Examples include: 3D molecular scaffolds with tuneable functionalities for applications in catalysis and high-specificity sensors (Addicoat); Perry's Biomolecular Materials Interface Research lab, which works at the boundary between biomolecules and other materials (recognised by the Royal Society Wolfson Merit Award); and the *iSMART* (Innovations in Surfaces, Materials and Related Technologies) facility of Stevens, Koutsogeorgis, and Kalfagiannis, which specialises in the custom-modification of surfaces, such as the self-assembly of nano-particle arrays with optical/photonic properties (e.g. for anti-counterfeiting applications). Our newest hire (Rahmani) in this area adds capabilities in nano-sensing and nano-materials, recognised by Royal Society and UKRI fellowships.

- **Smart Technologies** (developing from Imaging and Sensing in REF2014) is an approach for innovative engineering solutions that makes use of embedded sensors and control to produce truly responsive systems and materials. Examples include: smart wearables which unobtrusively collect data for healthcare and competitive sport applications (Wei, Faulkner in C24); arrays of vibration-sensors deployed in honeybee colonies to monitor swarm health and inform decision-making (Newton, Bencsik in C14); and the human factors lab, championed by Mansfield, which focusses on approaches to optimising human performance and well-being in the context of increasingly automated cyber-physical systems, including projects on autonomous vehicle occupants, aircraft, surgery expertise, and human-autonomy teaming.

- **Medical Technologies** (developing from Bio-materials and Materials Engineering in REF2014) describes the application of modern engineering and materials design to medical science. Examples include: tissue engineering for biomedical implants and regenerative medicine (Reinwald); bespoke 3D printing of composite bio-compatible materials for bone replacement (Siegkas); electrospinning nanofiber materials for wound dressing (Stevens); and breakthrough therapies, devices and technology to repair, augment and regenerate damaged tissues (Hunt).

This structure, and the supporting infrastructure investment, is summarised in the figure below.



These groups reflect a balanced approach to hiring and staff development, each hosting a leading distinguished or senior professor (Evans, Perry, Mansfield and Hunt) as well as early and mid-career researchers (see §2.2.1). Within the framework of the four groups, smaller labs or teams are encouraged to develop as bottom-up collaborations.

1.2 Research and Impact strategy

1.2.1 Achievement of REF2014 research strategy

In REF2014 we aimed to promote excellence in our engineering research via: (i) a new cross-disciplinary research facility with embedded industrial engagement and prototyping laboratories; (ii) growth of research and support staff; (iii) growth of international collaborations; and (iv) expanding our postgraduate courses. These aims have been achieved by:

i. Investing ~£50 million in UoA-focussed buildings (see §3.3) including the Interdisciplinary Science and Technology Centre (ISTeC, £11m, 2018), a new Engineering building (£23m, 2019) and the Medical Technologies and Innovation Facility (MTIF, £23m, 2020, §1.2.2, §1.2.3, §3.2).

ii. Creating 20+ new research-active academic staff positions including two research-intensive early-career positions (§2.1.3). New support staff include two industrial liaison officers, six technical support staff in the Engineering building, a technical lead of our imaging suite and two technical support staff strengthening existing services.

iii. Growth of international collaboration such that the majority of our research publications in this REF review period have at least one international co-author (source: Scopus/SciVal, 57% in 2020, compared to 37% in 2014), and academic hires in the period have been mainly international, enhancing our research network with their collaborations.

iv. New postgraduate courses including integrated-Masters MEng courses and the research-intensive degrees of MRes in Medical Imaging and MRes in Physics. These complement pre-existing postgraduate courses in Chemistry, Analytical Chemistry and Advanced Materials Chemistry, and reflect our established strengths in research-informed teaching.

A suite of School-wide, long-term staffing initiatives aimed at increasing all research-active staff time for research is detailed in §2.1.1.

1.2.2 Achievement of REF2014 impact strategy

In REF2014 (REF3a), we aimed to: (i) Promote diverse end-user engagement of our research in Imaging/Sensing and Materials; (ii) Increase industrial collaboration, including impact fellowships and industry-linked postgraduate courses, and; (iii) Build industry collaborations, including through developing our iSMART advanced materials R&D hub infrastructure, resources and networks. These aims have been achieved by:

i. Our significant and diverse impact in the REF period, showcased in our Impact Case Studies. These range from keeping an estimated 5.56 billion person-journeys of the flying public safe in the US alone using NTU-enabled novel X-ray security screening systems, through enabling the Louvre's successful 2016 restoration of Leonardo da Vinci's 'Saint John the Baptist' that employed NTU's novel optical imaging instruments, to providing the 'brain' of the 17 metre metal 'Hive' immersive artwork that has brought honeybee conservation issues to over 5 million visitors of the 2015 Milan World Expo and Kew Gardens.

ii. Our staff have secured 13 Innovate UK projects, including KTP, Feasibility, and Innovate UK/EPSRC R&D grants, with NTU as lead or participant organisation. Through these we have partnered with 19 companies across 8 English regions on projects worth £3.0m in total (£701k NTU income). On KTP projects (§3.1) high-calibre associates enable technology transfer, supported by NTU academic expertise, with, for example, an associate permanently employed after a KTP with Cole-Parmer Ltd. The new industry-

linked MEng courses (§1.2.1) were developed in consultation with 26 businesses across Biomedical, Electronic and Sport Engineering industrial sectors.

iii. We secured £9.7m competitive D2N2 Local Enterprise Partnership (LEP) Regional Development co-funding to support the building of a new Medical Technologies and Innovation Facility at the University, TRL1-TRL2 Research Centre, and on the Boots Enterprise Zone, TRL3-TRL6 Technology and Prototyping Centre (§1.2.1, §1.2.3, §3.2). MTIF was conceived by industry sector professionals from NTU's strategic partners, MediCity Nottingham, Medilink East Midlands, Cheata Clinical Trials, Derby Teaching Hospitals NHS Foundation Trust, Nottingham University Hospitals NHS Trust, and Boots plc. Market insight was gleaned from 25 interviews with CEOs and MDs responsible for business growth and new product development of D2N2-based healthcare companies. Senior academic staff from iSMART contributed significantly to the bid, planning, and implementation stages.

1.2.3 Enabling and facilitating impact

The UoA has provided a range of sustainable mechanisms to help incubate optimal impact of our research at all stages, and we have targeted resources including funds, studentships and sabbaticals, towards prioritising cases for support with planned impact routes. Examples include:

- The realisation of impact of Evans' research on aviation safety (HALO X-ray Technologies Ltd Impact Case Study) was underpinned by extensive NTU support and investment, including work to patent the technology and arrange licensing terms (IP Manager), and spin-out the company including developing the business model and launching the company in the MediCity business incubator supported by NTU loans. The underpinning research was supported by 3 NTU-funded PhD studentships.
- The realisation of impact of Bencsik and Newton's research (The 'Hive' Impact Case Study) that produced machine-learning algorithms analysing real-time honeybee colony activity on the creation of major competitive sculpture installations (the 'Hive') at Milan Expo and Kew gardens and in the Middle East ('Project B'), was supported by travel funds, sabbatical and teaching buy-out, and two funded PhD studentships. Funding and technical and estates resource enabled the custom-built apiary infrastructure.
- The realisation of impact of Liang's research (Cultural Heritage Assets Impact Case Study) was supported with funds for bridging skilled research staff between external/industry contracts to retain a senior research fellow which provided critical stability of skills and expertise for impact development.
- Morris and Newton's development of a new class of MRI/Radiotherapy-compatible patient-positioning boards using natural fibre composites was supported by seedcorn funds from NTU's Enabling Innovation Programme and validated using our new MRI Imaging Facility (2016) leading to Innovate UK funding with project partner Medibord Ltd. Commercialisation was enabled by sabbatical/impact leave and supported by the School Commercialisation Officer, with IPR protection. The first sales, since March 2020, have improved the treatment of hundreds of cancer patients, and collaborations with Ohio State University and OncoRay (Germany) have led to auxiliary products.

Other examples include: NTU Strategic Theme (§1.3) seedcorn support, e.g. Zhang's human trial of belts to monitor foetal motion; staff recruited from technology translation institutes, e.g. Afazov from manufacturing technology centre catapult; equipment support for Stevens' applications of electrospinning in biomedicine, matched by external funds and leading to two patents, IP commercialisation and Innovate UK funding; contributions to site-licenses of ANSYS modelling software, along with industry workshops/seminars on its applications, leading to bespoke packages and a network of international industry partners (e.g. Bridgestone Japan).

The impact showcased in the case studies from our more mature groups reflects our pedigree of excellence in imaging and sensing. These, and further examples in §4.2, also reflect our strong commitment to interdisciplinary research.

1.2.4 Research and Impact objectives

As we consolidate from a period of growth, our overarching ambition is to use this expansion to extend and enhance our international reputation for creative engineering and engineers. To this end, we will:

i. Develop innovative technologies towards future manufacturing and engineering practice.

For example, Rahmani's £1.2m UKRI Future Leaders fellowship will use photonics and nanotechnology to upgrade glass surfaces to NIR-imaging devices, while Evans' new £1m EPSRC project will apply sporadic sampling to improve the efficiency of X-ray diffraction to identify powders and soft materials in next-generation imaging systems for security. The infrastructure investment (MTIF/ISTeC/SWIFt) supporting our Medical and Smart Technologies groups is further aimed at developing a >£4m/year income stream via contract research and industry-sponsored projects.

ii. Foster complementary pathways to impact by academic, industrial and civic partnerships.

For example, with match-funding from the D2N2 local enterprise partnership and working with the Digital Catapult, NTU is investing £800k in a Smart Wireless Innovation Facility (SWIFt, see §3.3) as part of our 'Smart Campus' initiative. SWIFt will be a centre for developing 5G and other wireless applications and will create a testbed for researchers and enterprise. To support this facility, and to shape the research direction of the Smart Technologies group, we will establish a new Chair in Digital Engineering Innovations.

iii. Exploit our interdisciplinary strength to develop novel applications of engineering problems.

For example, a £486k project newly awarded to Perry combines research in microbiology, engineering and materials to enable the tailoring of future functional composite materials based on fungal mycelia. Similarly, recent AHRC capital investment of £898k will enable Liang to stay at the forefront of heritage science research and benefit national and international collections. This is further supported by NTU's first Research Peak in *Cultural Heritage* (£500K pa investment, REF5a), with Liang as co-lead, which brings together state-of-the-art scientific methods for analysing and preserving heritage with an understanding of the cultural context, involving collaborations in over 20 countries.

iv. Address societal grand challenges such as aging society and sustainability.

The investment in MTIF will accelerate the translation of our Medical Technologies research towards personalised medicine improving the quality of care. This ambition will be achieved by provision of state-of-the-art research and incubation facilities and by linking researchers to industry and clinicians. Our recently awarded BBSRC Doctoral Training Partnership with the University of Nottingham (§2.2) will provide further investment to this area. We will also establish a new chair and group in Sustainable Engineering to address energy challenges in the context of diminishing resources.

v. Recruit and support excellent researchers, embedding diversity, inclusion and innovation in our ways of working.

Our objective is to recruit, support and retain the highest quality staff aligned to our research groups, with a focus on developing early career staff to research leadership. This is particularly important with the planned growth of the Engineering Department by over 20 more academic staff to 2025.

1.3 Approach to Interdisciplinary Research

NTU proactively supports inter-disciplinary approaches to research and has structures that encourage collaboration across academic disciplines. At the forefront of these are NTU's Strategic Research Themes, supported by targeted resources totalling £1.8m across the REF cycle (see REF5a). These bring together cross-disciplinary teams to collaborate on innovative responses to the challenges faced by stakeholders.

The structure of IMEC, including engineering as well as allied branches of the applied sciences, naturally lends itself to encouraging interdisciplinary and multidisciplinary research. We do this in a variety of ways, including:

- Our research groups are cross-departmental by design, and smaller teams are encouraged to follow this direction. As typical examples: our *engineering design and simulation* team provides a forum for the exchange of insight and technical expertise in modelling research from the density functional theory of interfaces (Shuttleworth, physics) to the search-based design of functional materials (Addicoat, chemistry) and the simulation-based design of 4D metamaterials (Bodaghi, engineering) whereas our *smart wearables* team combines approaches from physics (Newton/Morris, designing sensing elements into yarn) and engineering (Yang/Navaraj, incorporating flexible electronic circuits into clothing) members.
- Similarly, our shared research infrastructure (§3.2) is aimed at supporting excellent research across the School, regardless of discipline; most labs have an open-door policy of at-cost use by other researchers. This is facilitated by technical support staff, training and equipment which operate outside any specific department. For example, the Imaging Suite, and its technical manager, supports the characterisation of novel biomaterials, plasmonic sensors, colloidal materials and so on.
- To encourage cross-disciplinary discussion and collaboration, the School's Science and Technology Annual Research (STAR) conference brings together speakers from across the STEM disciplines, with high-profile external speakers and a trade/employment show.

Reflecting this support for multidisciplinary research, IMEC has active collaborations with the Schools: of Animal, Rural and Environmental Sciences (Burton, silica supplements in animal feed); Arts and Humanities (Hodgson, materials analysis of historical manuscripts); Architecture, Design and Built Environment (Al-Habaibeh, smart buildings); and Art and Design (Downes, image processing). NTU Engineering is cross-disciplinary across a wide range of arts as well as sciences.

1.4 Strategy for an open research environment

Recognising the value of open access to the outputs of publicly funded research and anticipating the move towards an ever-more open research environment, IMEC's open-research strategy combines basic requirements with additional encouragements and incentives to develop a culture of open research.

Specifically, we work to ensure that all research outputs are made open access via our institutional repository (IRep); monthly summaries are compiled by library research support, such that oversights may be addressed promptly. We aim for open access for all publications, including reviews, book chapters, etc.. Many academic staff also use preprint servers to increase their work's reach (e.g. ~65 arXiv preprints deposited between 2014-2020). Support and advocacy around open research are provided by the library with all staff made aware of their responsibilities, and the available resources, at induction.

We also actively encourage staff to go above and beyond these minimum requirements. We have been supported in this by the NTU Open Access Publication Fund, which has provided immediate gold open access to selected outputs, prioritising expected high-quality contributions. Within IMEC this fund has invested £112k in supporting 55 open access publications. Additionally, publisher deals (e.g. Wiley, Springer, SAGE) allow NTU authors to publish via the gold route at no cost.

Furthermore, the UoA works with the University leadership to encourage appropriate data management and sharing. In accordance with the Concordat on Open Research Data, we require a research data management plan for all new research projects. Library services offer training for and liaise with academic staff and assist in the planning and implementation of funding opportunities with data management requirements. Again, we actively encourage staff to go beyond any required needs. As examples: Addicoat, Benjamin and Wei routinely publish open

data supplements alongside their papers, including prominent work (Nature Comms. 7:12325, 6:7786; RSC Adv. 7:48754;); Goehring has published environmental data on a public repository (doi.org:10.5194/essd-12-2881-2020), and has work used as an exemplar in a *Communications Physics* editorial on open science (doi.org:10.1038/s42005-020-00403-4); and Addicoat, Wei and Vanheusden publish open-source codes, or code incorporated into open software packages.

1.5 Supporting a culture of research integrity

We are committed to the highest standards of research integrity and the relevant professional frameworks including the Concordat to Support Research Integrity. Matters relating to research integrity, including research ethics, Code of Practice for Research, and a Responsible Metrics Statement are overseen centrally (see REF5a) and managed locally. Robust scrutiny of projects requiring ethical approval undertaken by staff and PGR candidates within the UoA is overseen by specific School of Science and Technology-wide Research Ethics Committees (invasive human, non-invasive, animal, GMO work). This ensures projects are scrutinised from different disciplinary perspectives. Training resources are available to all staff and students in the form of online modules which cover different aspects of research integrity. This central resource complements training arrangements at local level, which are designed to meet the needs of specific committees. Our library Research Data Management Officer provides advice and support on GDPR and safe and secure data archiving. Training on good research practice is promoted as part of ongoing professional development. GDPR, equality and diversity, and unconscious bias training are required for all staff members.

2. People

2.1 Staffing strategy and staff development

We aim to strategically recruit and thoughtfully develop strong research-active staff at all stages of their career. We ensure a positive, diverse and collaborative working environment, where staff are motivated, performing highly and empowered to realise their career ambitions. This approach is informed by and implements the principles of the Concordat to Support the Career Development of Researchers and the Vitae Researcher Developer Framework.

The success of our strategy is evidenced by our excellent staff retention and promotion record, our ability to attract award-winning world-class researchers, and high levels of staff satisfaction.

2.1.1 Staffing and Recruitment policy

Taking advantage of a period of rapid growth and investment has allowed for a hiring strategy aimed at (i) enhancing the proven potential of our two established groups (imaging and advanced materials) while also (ii) building up sustainable teams in medical and smart technologies, and (iii) maintaining our characteristic interdisciplinary strength. This strategy also makes best use of concurrent expansion of buildings and infrastructure (§3.2). Highlights include: launching a general Engineering Department, whose members join teams of established applied scientists working across disciplinary boundaries; the recruitment of key staff with experience in the translation of research from academic to industrial/applied environments (§1.3); the creation of independent research fellowships intended to foster the next-generation of research leaders; and strategic high-level appointments intended to guide and inspire our growth in medical and smart technologies.

During the assessment period the UoA has grown significantly, trebling in size from 15 staff (14.6 FTE) in 2014 to our current 48 members (47.2 FTE). Mostly this results from the new general Engineering Department, with its first courses delivered in 2017-18: since 2016 we have added approximately 3-5 new academic staff positions in engineering annually (currently 18 Category A staff, including two sports-engineering academics returned in C24).

This growth of the UoA has been guided by staffing policies including:

- Recruitment of world-leading, high-level staff to provide research leadership: Mansfield (2016, from Imperial) to head the Engineering Department with his unique vision of human factors engineering; Hunt (2017, Liverpool), who specialises in biomedical materials and tissue engineering, as a Head of MTIF and lead of NTU's Medical Technologies and Advanced Materials Research Priority; Biggs as Head of College (2018, Dean of School of Science, Loughborough) to champion equality issues (e.g. lead in NTU Athena SWAN) and international networking; and Rahmani (2020, Australian National University) who adds new award-winning directions to our materials group involving tuneable nanostructured materials.
- A School initiative to expand academic 'headroom' and increase the average allocation of research time for research-active staff via additional staffing, without commensurate increases in teaching. This resulted in two new positions aligned with our materials group, in soft and advanced materials (Goehring, from Max Planck Society and Volodkin, from Fraunhofer).
- The creation of a new role of academic associate, a 5-year position that combines PhD training with teaching duties. These roles provide training for future leaders outside the traditional research-intensive academic roles and add teaching capacity to the School.
- An Independent Research Fellowship programme with two UoA-relevant hires (Addicoat, previously at Universität Leipzig, and Kalfagiannis, retained from a Marie Curie Fellowship) in advanced materials. This early-career opportunity is also intended as succession planning, for replacement of retiring senior staff with new ambitious and high-achieving researchers (§2.1.3).
- Impact-targeted hires of staff with experience of academic/industry crossover, such as Abdelgaied (medical devices, e.g. Tissue Regenix), Afazov (High-value Manufacturing Catapult Centre), Richards (QinetiQ/Ministry of Defence) and Simpson (ANSYS).

On the census date IMEC consisted of 9 professors (8.6 FTE), 10 associate professors/principal lecturers (10 FTE) and 29 lecturers/senior lecturers (28.6 FTE). Thus, the UoA retains a balanced structure with good staff representation at all levels, allowing for the long-term sustainability of career progression. Excepting our independent research fellows ('tenure-track' positions), all Category A staff are permanently employed. The UoA also has high levels of staff retention. For example, of the 15 staff returned in REF2014, 12 remain at NTU. Of these, the majority have been promoted during the intervening period: one to senior lecturer; three to associate professor; one to principal lecturer; one to professor; and two to Distinguished Professor.

2.1.2 Staff Development Strategy

NTU operates a system of Academic Career Pathways (see REF5a) and through this ~60% of staff in the School of Science and Technology have significant responsibility for research and thus a core allocation of time protected each year to engage in research, as reflected in their individual workload plan. All staff, including research, support, and technical staff, participate in an annual appraisal cycle with their line manager that includes three formal meetings per year to set and review objectives and workload. Newly hired staff are typically hired with a one-year probation period that follows a similar cycle, but with an additional independent mentor to guide them through the process of integrating into the University and IMEC.

Outstanding research accomplishments by our academic staff are celebrated and recognised by the University in various ways including the Vice-Chancellor's Outstanding Researcher Award scheme. Academic staff in the UoA are well-represented in these awards, including Chappell (early career researcher award, 2016), Addicoat (early career researcher award, 2019) and Liang (established researcher award, 2020).

Within the UoA, all research-active staff below professorial level are paired with a research mentor. These relationships are designed by mutual agreement and typically involve overlap in research areas within the same group, adding to the sustainability of the research environment. With their

mentors, staff develop Individual Research Plans that identify short-term goals to feed into appraisal objectives and longer-term goals in relation to career progression. Mentors also help ECRs identify funding opportunities and develop funding applications, as per our early career research policy (§2.1.3).

Staff have access to a wide range of development opportunities. These are coordinated through NTU's Researcher Development Framework and aligned to Vitae, which champions the personal, professional and career development of research staff. Over 50 modules include: essential learning for all staff (e.g. equality and diversity, GDPR, unconscious bias, health and safety); School-specific development coordinated by our research support librarians (e.g. data management and open access, maximising research impact); research leadership training including workshops on postgraduate research supervision and the design of independent research programmes; workshops and individual support for HEA fellowship applications; health and well-being workshops, and so on. Additionally, a themed quarterly researcher forum allows for a rolling induction of topics to staff; past themes include the Concordat for the Career Development of Researchers and Publishing and Open Access.

Staff survey results consistently show high levels of staff satisfaction with our environment. For example, in the 2018 survey, in our main constituent departments, over 90% agreed with statements of positive job satisfaction ("*Generally, I enjoy my work*" or "*My work gives me a sense of personal achievement*") and collegiality ("*I feel valued by my colleagues*" or "*I am satisfied with the support I get from my work colleagues*").

2.1.3 Early Career Researcher (ECR) Support

Given our recent expansion, early career researcher (ECR) support is particularly important to the long-term strategy and the sustainability of the UoA's research. A wide range of support for ECRs is available, including:

- Tailored aspects of the appraisal cycle and staff development opportunities (see REF5a), including an Early Career Academic Development Programme and a Winning Grant Funding Programme;
- New ECR staff are paired with both a research mentor (from their department/research group) and a teaching mentor;
- IMEC regularly contributes to the start-up costs of researchers, to help establish their research capability, including nine grants totalling over £65k in the REF period. The School allocates funds directly for ECR research support, e.g. £250k in 2019/20 academic year;
- ECRs can revitalise a research stream with new expertise and techniques. Thus, they are prioritised with new equipment through a capital investment programme (School-wide ~£1M/year, see §3.2). For example, Khalid secured his first EPSRC project grant (£60k) based on capital investment in our robotics lab;
- ECRs are prioritised in internal competitions for research funds, to help them become self-sufficient in grant income, e.g. funding for a six-month postdoc helped develop Benjamin's successful EPSRC First Grant proposal;
- Similarly, ECRs are prioritised with studentships, and senior academics are encouraged to pair with ECRs on such bids and on PhD supervision teams; and
- ECRs benefit from reduced teaching load over the first three years of starting a new position, with additional protected research time in their academic workload.

An example of our ECR strategy is the Independent Research Fellowship programme. These 5-year ECR roles with reduced teaching (initially 50 rising to 100 contact hours/year) and dedicated research support (£10k/year) are intended as 'tenure-track' routes to permanent lectureships. Of our two fellows, hired in 2016:

- Kalfagiannis adds long-term sustainability to our advanced materials group. His rapidly developing research leadership includes conference organisation, guest editorship,

multiple PhD supervisions, and a visiting academic position (Ioannina). His research in thin-films received £200k of NTU capital investment (IR Spectroscopic Ellipsometer system, also developed into MSci lab demonstration), and attracted a KTP to exploit security applications of photonics (Opsec Security) and a Competitive Research Grant (KAUST, project budget $1.5M) to develop photonic processing of metal-oxide thin-film transistors.

- Addicoat revitalises our computational-focussed engineering design and simulation team and brings focus to a cluster of research excellence involving the smart design of materials. He was supported by additions to our high-performance computing (HPC) facilities in 2017 and has been primary supervisor on two PhD projects. His work is prolific and high-profile (>40 peer-reviewed publications since hire, including in *Science, Nature Communications, Angewandte Chemie*) and he has recently attracted an EPSRC New Investigator Award and a Royal Society International Exchange grant.

Postdoctoral researchers are supported by a similar range of professional development opportunities as other ECR staff and participate in NTU's Researcher Development Framework and Appraisal cycle. Additionally, to assist their transition into a full academic career, they are guided by regular career development meetings with senior academic staff and can take Careers and Employability Service courses. UKRI-funded researchers teach up to 3 hours per week and are supported by experienced module leaders in building their experience from project and lab supervision to developing and delivering lectures and examining on taught modules. The UoA's approach to attracting and supporting high-quality postdoctoral researchers can be demonstrated by the career prospects of former researchers, including e.g. Ladak (lecturer, Cardiff); Roach (lecturer, Loughborough); Wells (lecturer, Edinburgh); Baldwin (lecturer, NTU); Hamlett (outreach officer, Birmingham); and Evans (systems engineer, Rolls-Royce).

2.2 Research Students

Postgraduate researchers (PGRs) are an integral part of our research culture. As with staff numbers, our PGR programme is expanding, with 39 PhDs awarded in the census period, compared to 27 during the last period. As with staff numbers and grant income, PGR intake has increased more rapidly in recent years, with 51 PGR candidates currently in progress with a Director of Studies in IMEC.

This growth of a dynamic and sustainable population of research students has been supported by a diverse strategy of securing PGR funding, including:

- NTU PhD Studentships are competitive, fully-funded scholarships that cover tuition and stipends and have supported 35 PGRs in our UoA since 2013.
- NTU's Match-Fund scheme (launched 2016) covers half of PGR costs, where an external sponsor contributes the other half. It is particularly attractive to industrial and applied partnerships in IMEC, with five funded projects to date (see §4.2).
- Industrial CASE awards (e.g. Brown with Merck for liquid crystal devices) and projects fully funded by industry (e.g. Perry with AbVista for exploiting silica as nutritional supplement).
- BBSRC Doctoral Training Partnership, led by the University of Nottingham. Aligned with NTU's Medical Technologies and Advanced Materials strategic theme, this £15m programme started in 2020. Proposed projects from our UoA include functional scaffolding for tissue regeneration (Volodkin) and modelling age-related bone loss (Hunt).
- The national Doctoral Training Alliance (DTA) Energy and Applied Biosciences for Health programmes have funded several PhD projects (Gao, Volodkin and Giannakidis).
- AHRC studentships for heritage science applications of our imaging group, involving the National Gallery (material properties of varnishes), the British Museum (conservation of vitreous materials) and the British Library (maritime silk road).

Support for the PGR community is coordinated by the Doctoral School (see REF5a) and School-level Postgraduate Research Tutors. This includes:

Recruitment. To ensure a fair, consistent approach the School's PGR tutor, or deputy, normally chairs all PGR interviews. These chairs are trained in this role, including unconscious bias training. Applicants are expected to have a master's degree or a first-class honours degree.

Supervision. Supervisory teams include at least two NTU staff with experience of at least two PhD completions between them. All supervisors attend a two-day training course and are invited to meetings of the School Supervisors' Forum, which supports best practice in the supervisor community. External supervision is possible and encouraged for industry/match-funded PhDs.

Monitoring. Students typically meet their supervisors weekly and prepare at least 12 documented supervision-meeting reports per year. Progress is formally monitored via a supervisory panel and independent assessor, with annual monitoring as well as key deliverables around Month 6 (Project Approval) and Month 18 (Transfer from MPhil to PhD).

Training. Training opportunities are covered during induction with the School PGR tutor and postgraduate representative and reviewed as part of annual monitoring. The NTU Doctorate Plus Programme (see REF5a) maps PGR training to the Vitae Researcher Development Framework, the requirements of the UK Research Councils and the Quality Assurance Agency.

School-specific training supplements NTU-wide opportunities, such that PGRs can create bespoke packages of activities to support their development. This includes workshops in research methods, report writing, project management, research data management, and equality and diversity awareness. An effective researcher course is targeted at first-year PGRs, and additional English classes for researchers with English as a second language. Training in research methods can include specialised equipment (e.g. AFM, SEM/TEM, 3D printing) and software (e.g. Matlab, ANSYS, CAD). The School also coordinates subject-specific health and safety training.

Throughout their degrees, PGRs have opportunities to share their research and develop presentation skills, including:

- In our School-wide STAR conference (§1.4) PGRs typically present a poster in their first year and a talk in their second. In 2020 presentations were adapted to an online/virtual setting, incorporating a 3-minute thesis competition.
- All departments run weekly seminar series, with a mixture of invited external and internal speakers from engineering and related disciplines. PGRs are invited to present their work at a full seminar in their third year.
- Many of our teams and labs coordinate their own research meetings, with informal opportunities for PGR presentations, such as practice talks for conferences.

The success of our PGR strategy can be seen in our high level of on-time thesis submission rates (89% for 2017/2018) and the overall satisfaction of PGRs in the School, as tracked in the Postgraduate Research Experience Survey (PRES), which has averaged 82% since 2014.

2.3 Equality, diversity and inclusion (EDI)

Our School is a vibrant place to work, enriched by the diversity of perspectives, cultures and backgrounds brought by our students, staff, visitors, and local, national and international partners. Within IMEC we recognise that diverse teams encourage more creative and innovative solutions to engineering problems and, supported by the Royal Academy of Engineering, we recently appointed a Visiting Professor in Human Factors: Innovation Through Diversity, to apply human factors engineering to drive change through inclusive, mission-led innovation.

The University was awarded the bronze Athena Swan charter mark in April 2019 (see REF5a) and targets a silver submission in 2023. Supporting this, our School strategy aims at departmental Athena Swan submissions from 2022; application teams are currently conducting reviews, including cultural surveys on gender identification, promotion prospects and support, as a basis

for developing an action plan for moving towards gender equality. Our School's Athena Swan Champion leads these efforts and coordinates School-level EDI activities including nominations to the Advance HE Aurora programme (6 in the School in REF2021), events for International Women's week, international women in engineering day, Black History month, and LGBT History month, the installation of an on-campus nursing room for nursing mothers, and maintenance of an EDI intranet with links to staff networks, policies and resources. Our Engineering course manager (Smith) is also a trustee of the Women's Engineering Society, and we share its aim to support and inspire women to achieve as engineers, scientists and leaders.

Recruitment across the School has transitioned, through gender decoding of recruitment materials and mixed-gender interview panels, to attract a more diverse staff pool. Staff training improves knowledge and understanding of equality and diversity within the workplace and we have introduced mandatory unconscious bias training for all staff. Across all academic and research staff in our School, 32% identify as women (28% in 2014), 16% identify as Black Asian and Minority Ethnic (13% in 2014), and 4% declared with a disability in 2019 (4% in 2014). We support (and, within IMEC, have reached) NTU's institutional target to increase the representation of women within the professoriate to 35% by 2022. Furthermore, we encourage a flexible and inclusive approach for staff working from home, or remotely. The Support of Academic Returners (SOAR) scheme funds up £5k following a period of caring-related leave to support career pathway development (e.g. one recipient bought out teaching time to finish two papers), while IMEC has prioritised several internal funding requests related to flexible working arrangements or parental leave (*e.g.* ~£5k contract extensions or variations).

Staff perception of EDI issues is very positive. For the main departments composing IMEC, the 2018 staff survey showed 84-100% agreement with *all* statements of equality of opportunity and protected characteristics, including "*I believe the University is committed to equality of opportunity for all of its staff*" (93%) or "*I feel the University acts fairly, regardless of protected characteristics regard to development opportunities*" (92%).

Finally, our REF submission and output portfolio were developed in accordance with our institutional code of practice. Category A staff were advised by email about the window for the voluntary declaration of Individual Staff Circumstances, and the University's Head of Equality, Diversity, Inclusion and Wellbeing provided a Q&A session and debrief for IMEC.

3. Income, infrastructure and facilities

Reflecting the recent period of strategic growth of our research base, the UoA has benefitted from significant investment in infrastructure and facilities. This includes over £50m of new buildings and research labs, targeted to our newer medical and smart technologies groups. This investment has started to see returns in increased grant capture and external income, in line with our forward-looking strategy prioritising a sustainable research environment (§1.2).

3.1 Income

The UoA attracts a diverse stream of research income, reflecting its multidisciplinary and international strengths. In addition to the research councils (AHRC, BBSRC, EPSRC and STFC), we have received significant investment from the US Air Force and Department of Homeland Security, the National Grid, Merck and Bridgestone, KTP agreements and match-funded studentships (§2.2/4.2) with industry, and competitive in-kind support, particularly from X-ray/neutron facilities. As a result, the average annual research income in the REF period has risen to £1.7m (from £1.4m/year for REF2014). Much of this growth has been within the past three years, reflecting successful grant capture from new hires in the Engineering Department; in 2020 staff in our UoA secured £4.3m in external funding.

Exemplary of the multidisciplinary nature of the UoA's impact, and our network of collaborations, we currently participate in four EU Horizon 2020 projects (€19.7m combined value with £1.2m to NTU):

- ComfDemo (Mansfield, Vanheusden and Faulkner in C24) is a collaboration between NTU, VHP Human Performance and German research institutes. Using Mansfield's expertise in human factors and ergonomics, it aims to improve comfort on turboprop air travel.
- B-Good (Newton, Bencsik in C14 and Chuzhanova in A03) involves 17 partners in 13 countries, succeeding the FP7 Swarmonitor programme (REF3 Impact Case Study). It seeks to use a broad spectrum of data collection (smart technologies) to monitor hives for health and risk assessment.
- TopSpec (Kilgour) involves 8 partners and aims to develop a ground-breaking top-down tandem mass spectroscopy platform capable of rapidly sequencing antibodies and other large proteins/molecules. Involving eight partners and industries, this applies our medical technologies focus towards solving one of the greatest challenges in the top-down mass spectroscopy of large molecules.
- IPERION HS (Liang) is a consortium of 67 institutions from 23 countries contributing to a pan-European research infrastructure on heritage science, offering training and access to a wide range of high-level scientific instruments, methodologies, data and tools for advancing knowledge and innovation in heritage science. NTU participates via our ISAAC Lab providing mobile remote imaging and spectroscopy facilities (see REF3).

Evans' £5.2m US Department of Homeland Security contract has allowed for exploitation of a breakthrough in multiple-view imaging in the field of airport security (see REF3). The results, published in a series of *Optics Express* papers and protected by patents commercialised by spin-off company HALO X-ray Technologies Ltd, have enabled deployment of over 6,000 next-generation X-ray aviation security systems worldwide, with a follow-up test underway at Schiphol Airport.

Liang's £200k National Grid project has likewise applied our imaging focus to a new industry, specifically to the remote detection of corrosion during inspection of electricity towers and substations.

Perry's US Air Force Office of Scientific Research funding (2 awards, £1m total) has led to fundamental understanding of the events occurring at bio-materials interfaces. Combined with work on biomolecular binding on silica, it has led to numerous publications and has been taken up by Toyota, Samsung and Corning (e.g. anti-finger printing surfaces).

Knowledge Transfer Partnerships are another significant part of our research income strategy, with their particular potential for long-term impact. Following a concerted campaign to increase funding in this area, including regular School-led KTP workshops, the UoA has been successful in capturing Innovate UK awards worth £800k, including those with OpSec Security (Kalfagiannis, Koutsogeorgis), Cole-Parmer Ltd. (Fairhurst), Far-UK Ltd. (Chappell), Opus International Consultants Ltd. (Liang) and Tecquipment Limited (Simpson).

Reflecting the strengths of our Imaging group, we are also particularly successful in competition for time at advanced imaging facilities such as synchrotrons/neutron sources (e.g. ISIS/Diamond/ESRF/CLF), generating ~£400k of STFC research-income-in-kind and a match-funded PhD studentship that includes a further ~£180k of beam-time at the Diamond Light Source. More prominent results have included: development of a microfluidics goniometer utilising acoustic signals to rotate crystals (doi:10.1039/C7LC00812K), currently being installed at Diamond for general use; and elucidation of fractional crystallisation effects in colloids, allowing for novel routes to complex crystal formation (doi:10.1103/PhysRevLett.124.058003).

Finally, three of our ECR staff have attracted ECR-focussed funding, in the form of an EPSRC first grant (Benjamin, to design a new Lewis acid catalyst, and Chappell for stochastic modelling of

transport operators) or new investigator award (Addicoat, to develop flexible molecular framework materials). Other ECR successes include: Richards' Defence Science and Technology Laboratory award to develop human-autonomy working teams; Abdelgaied's collaboration with Leeds to study wear in artificial limbs; and Khalid's EPSRC/PepsiCo award to study occupational safety in the context of smart factories.

3.2 Facilities

New build: NTU has made significant infrastructure investments since 2014, commensurate with strategic growth in engineering and reflecting our research strengths. Three new buildings have transformed our Clifton Campus, designed to enhance research and research-informed teaching in the STEM disciplines in general, and in engineering in particular.

- The Engineering Building (£23 M, 4370 m^2, completed 2019) focuses on the 'Engineer of the Future', including facilities for applied research in Industry 4.0 and:
    - Houses extensive labs including: robotics/drone lab (e.g. sensors and coordination in drone swarms; industrial robots for human-robot automation); virtual reality suite (vehicle ergonomics; Bridgestone); biosensors suite (smart wearables); aerodynamics lab; fluids lab; mechanical testing suite; human factors suite with isolated recording lab (industrial psychology applications); mechanical workshop; 3D printing suite; sports lab (professional cycling; Huub); controlled environment chamber (human factors; sports engineering); biomedical engineering suite; medical engineering design suite (medical robots); and nano-photonics lab. These open-plan labs are designed around combining teaching and research opportunities in the same space, emphasising our commitment to research-informed teaching methods.
    - Acts as a centre for commercial activity and industry partnership in industrial digitisation, including companies such as Bridgestone, Siemens, PepsiCo, ANSYS and Fujitsu.
    - Will host the Smart Wireless Innovation Facility (SWIFt, see also §1.2.1), a 'living lab' that will have the capacity to connect up to a thousand devices and provide cross-technology capability that allows businesses and other users to test and develop 5G-enabled solutions. This will include workshop equipment, development sensors, data loggers and a rapid PCB prototyping system.
- The Interdisciplinary Science and Technology (ISTeC, £11m including £5m from HEFCE/Research England, 800 m^2 research wing, completed 2017) brings STEM subjects together to support collaboration between different subject areas, outreach activities, and industry engagement. Within our context, this includes:
    - Hosting the Imaging and Sensing for Archaeology, Art History and Conservation (ISAAC) laboratory, with a suite of in-house and mobile non-invasive optical instruments and users such as the British Museum and National Grid.
    - Providing spaces for collaborative and multidisciplinary research within one facility, including e.g. robotics lab (B11/B12), sports labs for biochemistry (A03/B12/C24), chemistry labs also used for materials synthesis, specialist computing labs including high-performance computing (B11/B12), and general IT resource areas. As with the Engineering building, these spaces are designed to encourage research-informed teaching opportunities.
- The Medical Technologies and Innovation Facility (MTIF, £23m including £9.7m from D2N2 Local Growth Fund, 3318 m^2 on two sites; completed 2020) aims to enable early stage research and development in medical technology and medical devices. It supports our activities in medical design (e.g. printable 3D cell scaffolds), biomimetics and biomedical implants (overlapping with A03). It provides an unprecedented new product development facility in the Midlands for partners to utilise, with an anticipated return of £3M/year of industrial or contract research opportunities (see §1.2.1). The Clifton campus

building supports early-stage innovation and impact-generation activities from our researchers, while the Boots Enterprise Zone building features an additional state-of-the-art manufacturing facility, focussing on industrial pilot projects.

Providing for a sustainable research environment, there have been regular opportunities for refurbishment of existing labs, for both existing and new staff including: £110k for refurbishment of applied chemistry lab; £20k for refurbishment of thin films lab to add microfluidics capability; £30k for expansion of ISAAC lab.

Communal research facilities: Our staff have free/at-cost access to state-of-the-art facilities operating on an open-door policy across campus, including expert training. Of particular relevance to IMEC are the imaging suite and computing facilities.

The UoA's strength in imaging is supported by a cutting-edge dedicated Imaging Suite, featuring: Atomic force microscope (Dimension ICON, 2016, £185k); Confocal microscope (Leica SP5, £17k upgrade, 2017); Scanning electron microscope (Jeol JSM-7100F + EDX, 2015, £250k); Transmission electron microscope (Jeol JEM-2010, replaced 2019, £640k). This suite is centrally financed and supported by technical support staff, including regular training sessions.

The School hosts two HPC clusters, for Linux (installed 2017/2018, currently 44 nodes of 16-20 cores each, up to 128 GB RAM / node and 30 TB storage) and Windows (installed 2016, 480 cores, half-funded by external income). The clusters enable computational work in advanced materials and medical technologies, including search-based design strategies for functionalised metal organic frameworks (Addicoat), molecular dynamics studies of chemical catalysis at interfaces (Shuttleworth) or lipid membranes (Robinson), and an industrial partnership with Bridgestone on modelling polyurethane foam at nano-scale. They have facilitated high-impact results (e.g. Nature Comms. 9:3757, 2018), allowed for prototyping code to be run on competitively allocated centralised computing facilities (e.g. Shuttleworth's £60k and Addicoat's £20k of computing time, UK Materials Chemistry Consortium) and supported EPSRC New Investigator submissions by Addicoat and Robinson.

Additionally, the School supports a capital investment programme of ~£1 million/year, to which IMEC recommends priorities. Spending has included >£1m of upgrades to the imaging suite equipment supporting incoming ECR's research strengths e.g.: Benjamin with NMR Spectrometer (£270k) and XRD replacement (£229k); Kalfagiannis with ellipsometer (£200k); Reinwald with biomedical engineering workstation (£89k); Bodaghi with materials testing rig (£42k); and Siegkas with high-speed camera (£47k). Another £900k supported the installation of the Engineering Building labs.

Other facilities include a broad range of research labs operating across campus. For example:

- The iSMART lab (now within MTIF) specialises in advanced materials, incorporating electrospinning facility, thin films fabrication with Class 100 clean room, plasmonic materials fabrication and metrology facilities.
- Our soft materials suite complements this with labs incorporating soft lithography and microfluidics fabrication workstations, rheology and fluids characterisation facilities, a liquid crystals research lab, and imaging systems (high-speed imaging, fluorescence microscopy, etc.).
- Our magnetic resonance imaging suite supports applied/medical research including our Medibord spin-off commercialisation (§1.3) and incorporates a Bruker Biospec MRI Scanner (£190k) and mobile NMR Mouse scanner (£25k).
- Bio-materials research is carried in two specialist biochemistry laboratories (170m^2). Multi-functional materials synthesis/analysis benefits from an organic synthesis facility (204m^2,16 fume hoods) plus a 103m^2 wet/dry lab equipped with materials NMR (Jeol 9.388T 400MHz), and X-ray diffraction systems.

3.3 Organisational and operational infrastructure supporting research and impact

Technical support is provided by a diverse team of about twenty technical support staff, including a School technical manager and three building-specific technical leads. Six additional technical support staff, recruited from industry, are embedded in the engineering building (with plans for 9 FTE at full capacity), providing jointly for research and teaching laboratory support. A dedicated technician runs our imaging suite and impact generation is facilitated by two commercial development officers. Applied research in the Chemistry and Physics departments is together supported by four research and four teaching-focussed technical support staff. The technical support team also operates a technician apprenticeship programme. The University is a signatory of the Science Council's Technician Commitment, which aims to support career development and sustainability for technical support staff in research.

To support ECRs applying for and securing their first competitive research grants/fellowships, NTU established a 'Winning Grant Funding' programme that has provided support including academic peer review and mentoring as well as masterclasses on proposal development, pathways to impact and developing external partnerships. There is also a School-specific mentor for early-career grants (e.g. EPSRC new investigator awards). The University's Research Operations supports grant application processes, facilitated by our 'Worktribe' research management platform, and Research and Strategic Partnership Development supports research grant and external partnership development, including Innovate UK and EU funding (§3.1, and see REF5a).

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

4.1 Research network

Global engagement is a strategic aim of the School (see §1.2). It is realised by well-subscribed schemes and opportunities including match-funded PhDs (§2.2), visiting fellowships for external academics, PGRs and industrial collaborators, internship programmes, funding for international research exchanges and bilateral agreements with strategic industrial and academic partners. Consequently, we support an exceptionally strong international network of collaborators. For example, most of our publications involve international co-authors, we maintain a wide portfolio of international and consortium grants (§3.1), our staff base is drawn from over a dozen countries, and 34% of our PGRs are recruited from outside the UK/EU.

Our visiting scholars programme (3-5 years, renewable) encourages high-profile networking, including industrial partnerships. Over the REF period this supported 28 visitors, including:

- Prof. Glen McHale (Northumbria, 2012-2017): work on complex fluids and superhydrophobic surfaces, resulting in 19 collaborative outputs including *Science Advances, Communications Physics, Physical Review Applied,* and *Materials Letters.*
- Dr. Rajesh Naik (Air Force Research Laboratory, 2012-2015), in collaboration with Perry's US Air Force funded work on biomaterials, which continues to generate high-impact publications in e.g. *Nature Communications* (2020).
- Dr. Ian Sage (Abelian Services, Technical Consultancy, 2014-2022), contributing to four co-authored publications on liquid crystals and manipulation of droplets with electric fields.
- Dr. Helen Dudfield (QinetiQ, 2020-2023, see also §2.3) is a leading technical strategist on utilising diverse engineering teams in addressing complex needs, and will mentor our human factors and digital human teams.

Other notable visiting appointments include David Wilkinson (Institute of Physics), Michael Waller (Nano Products Ltd), and Alan de Asha (C-Motion Inc). Similarly, our visiting students programme allows for hosting international PGRs, including those from Japan, Mexico and Spain.

Mirroring these hosting arrangements, research-active staff and PGRs have opportunities for national and international exchange and travel, supported both by NTU and external funding. Many staff have held visiting/guest positions elsewhere (e.g. Perry at MIT; Gao at Southwest University; Hunt at China Medical University; Goehring at Max Planck (MPIDS), Volodkin at Fraunhofer (IZI-BB)). A School fund supports travel to develop networks and build collaborations at specific research-intensive institutions (e.g. recently focussing on universities in Paris, Berlin, Barcelona). Academic staff collaboratively co-supervise PGR research projects at other universities including Leeds, Liverpool, Coventry and Heriot-Watt, and can allocate time for this supervision within our academic workload model (§2.1.2). Strategic bilateral agreements (e.g. research exchanges, networking events, joint PGR projects) also exist between target universities such as the Indian Institute of Technology Bombay and Panjab University. Finally, academic staff have developed their own international networks through external funding, including Addicoat (Royal Society, Russia), Goehring (Royal Society, Japan), Martin (Leverhulme and JSPS, Japan; Royal Society, China), Perry (DFG/Mercator Fellowship, Germany), Tranter (Institute of Mathematics, Italy) and Volodkin (Marie Curie/Humboldt; Germany).

Our Strategic Partnerships programme links NTU to 23 select partners from outside academia. For example, our partner BioCity complements the research facilities in our new MTIF building and offers applied research work opportunities for undergraduates and PGRs. Within IMEC, our Engineering and Digitalisation partners are AECOM (focusing on NTU's Smart Campus initiative and degree apprenticeships), Siemens (supporting research activities on smart meters, and Nottingham's Smart City ambitions) and Fujitsu (positively addressing societal challenges, co-creation, and Smart Campus). These partnerships extend across all levels of academic activity, including research-informed teaching: e.g. Fujitsu sponsored our 2019 Grand Challenge event, a 5-week opportunity to exchange ideas and build collaborations with industries, aimed at undergraduate students, and centred on the theme of smart technologies.

4.2 Research Impact and contributions

Our academic staff engage in diverse contributions to society and the economy and are supported in these activities by a range of competitive internal funding opportunities. Some exemplars, not already captured in our impact case studies include:

- Stevens' commercialisation track-record with Flexotronix (R&I director, 2018); Audition Therapeutics Ltd. (2015), SFZ Tech Ltd. (2014), and Nano Products Ltd. (2013). For example, Flexotronix developed conductive inks for hybrid electronics, RFID manufacturing and smart temperature-monitoring tags (with contract to QinetiQ).
- Perry and Burton (C14) developed silica-based dietary supplements for chicken feed to reduce lameness and poor bone health (with AB Vista providing £335k support): 11 feed trials have explored optimisation of delivery and biological impact, resulting in patents on the bio-silica source and a roadmap for further exploitation.
- Omurtag's clinical and ergonomic applications of EEG and brain-computer interfacing includes observing the mental workload of surgeons via EEG in operating rooms (Houston Methodist Research Institute) and training physicians to detect sub-clinical seizures using EEG (Downstate Medical Center, Brooklyn).
- Biggs has championed partnerships with local communities, including membership on: Making Mansfield Place; Discover Ashfield; Mansfield Health Partnership; BioCity plc.; and Nottingham Festival of Science and Curiosity boards. Afazov (Ashfield council) and Khalid (Newark and Sherwood District council) have also supported regional manufacturing bids.
- Chappell coordinated EU FP7 grant MHiVec (€1.9m) on modelling vehicle noise and vibration, with subsequent commercialisation of the DEA software tool (inuTech) contract research (Yanmar Co.) on full-scale tractor model, benchmarking tests (Jaguar Land Rover Ltd.) and KTP (Far-UK Ltd.) on virtual prototyping of automotive structures.

- Brown's long-standing relationship with Merck include consulting for ~£60k, contributions to PhDs, and work on tunable optofluidic devices (patent WO2017025167) and to solve 'mura' defect problems that can occur when filling LCD panels.
- Brown co-led NTU's involvement in the NUCLEUS Horizon 2020 project. This €4 million project (26 partners in 15 countries) brought Responsible Research and Innovation to life in universities and research institutions across Europe, China and South Africa.

Our policy of free/at-cost staff usage of our common base of technical equipment and services (§3.2), encourages proof-of-principle trials including industrial and academic partners. Industry access to facilities is supported by our Scientific Services to Industry (SS2i) initiative, staffed by two Commercial Technical Specialists, who have worked with industrial partners including 3K, BioPharma, Greenway Environmental, NVisiQ, OpSec Securities (kickstarting development into KTP), and Quotient. A database of School academic staff skills and expertise is used to facilitate commercial and contract research opportunities.

Our match-funded PhD programme (§2.2) also prioritises collaboration, industrial sponsorship and networking opportunities. Partners include: Diamond Light Source (Morris/Newton), including ~£180k in-kind contribution of beam time and resulting in new crystallography upgrades at their beamlines; Micromass/Waters Corp. (Kilgour), including ~£100k equipment contributions, to develop multiplex tandem mass spectrometry; Kymira Ltd. (Wang); and the Max Planck Society (Goehring).

Similarly, our undergraduate research internships allow the best undergraduate students at NTU to participate in research. This reflects our advocacy of research-informed teaching methods, with results that feed back into the curriculum and benefit the wider community. The University-wide SPUR internships (see REF5a) have offered 13 scholarships within IMEC since 2014, contributing to 5 research outputs. The Engineering Research Opportunity Scheme, Physics/Maths Undergraduate Research Scheme and summer internships in Chemistry now provide for over 50 such internships annually, or about one per research-active staff member. These interns are authors on at least 18 peer-reviewed publications (e.g. Phys. Rev. Lett. 121:184501, 121:064502; Dalton Trans. 47:11680; Int. J. Mech. Sci. 173:105451) and generated preliminary results for subsequently funded projects (e.g. Bridgestone; EU project ComfDemo).

The School and IMEC also support a range of community outreach activities, including the annual Nottingham Festival of Science and Curiosity and Science in the Park. We were one of three lead outreach providers within the £1m Chemistry for All (Royal Society of Chemistry) programme of widening participation, involving over six thousand young people, and which has set national guidelines for outreach providers. With BioCity we host an Ada Lovelace Day to inspire the next generation of female STEM scientists. Morris and Vanheusden collaborated on the *Sung Tieu: In Cold Print* exhibition at the Nottingham Contemporary gallery. Perry participated in a Royal Society pairing scheme with local MP Lillian Greenwood. Hunt is a STEMNET and MerseySTEM ambassador.

4.3 Indicators of influence, contributions and recognition

Reflecting their international profile, the academic staff of the UoA are well-recognised with positions of esteem, as well as external awards and prizes.

Highlights of staff prizes include:

- Evans' Royal Society Wolfson Fellowship (2018), Gabor medal (2017, Institute of Physics) and Times Higher Education Award for Outstanding Contributions to Innovation and Technology (2016), for his work on X-ray security technology, which was also integral to NTU's Queen's Anniversary Prize (2015).
- Perry held a Royal Society Wolfson Research Merit Award (2013-2017) in recognition of her studies of the biomolecule-mineral interface.

- Martin held a Leverhulme Senior Research Fellowship (2017) for his work in 2D and chiral superconductors, allowing for development of his Japan/China research network.
- Whittaker's Sir Paul Curran Prize for academic communication (2019, *The Conversation*) cites his "*compelling narratives … read 1.5m times and republished around the world"* and contributions to raising the public awareness of science.
- Rahmani's Royal Society Wolfson Fellowship (2020, Engineering nano-materials for optical technologies), UKRI Future Leaders Fellowship (2020) and ECR awards (Eureka Prize; Australian Optical Society; Optical Society of America; IUPAP).

Staff contribute to academic publishing as members of editorial boards, including *Scientific Reports* (Liang, Perry, Biggs), *Biomaterials* (Hunt), *Applied Surface Science* (Shuttleworth), *Ergonomics* (Mansfield), and have guest-edited special/theme issues in journals such as *Philosophical Transactions of the Royal Society, Chemical Engineering Science, Applied Ergonomics*. In more senior roles, Goehring is subject editor at *Proceedings of the Royal Society A;* Hunt is subject editor at *International Journal of Artificial Organs*; Biggs was executive associate editor of *Chemical Engineering Science; and* Gao is deputy editor-in-chief of *IET Nanodielectrics.*

Similarly, our academic staff have also helped organise e.g. the *International Conference on Materials Research and Nanotechnology*; the *World Congress on Materials Science and Engineering*; *Innowave* (2017, at NTU with ~50 industry delegates); and three of the *UK Fluids Network*'s special interest groups (e.g. Industry day at NTU on bio-inspired and smart surfaces, Ouali). Fairhurst co-founded the international *Droplets* conference (2013, subsequently biannual). Mansfield co-founded the International Comfort Congress (2017, subsequently biennial).

Other indicators of wider influence include: Hunt is honorary academic consultant of the Nottinghamshire Healthcare NHS Foundation Trust and chairs a Royal Society of Chemistry (RSC) committee; Biggs is a Fellow of The Institution of Chemical Engineers; Volodkin is a Fellow of the RSC; O'Neill was variously member and chair of the ERC FP7 systems and communication engineering panel, while Biggs chaired EPSRC Energy Storage Challenge panel; Perry sits on several RSC committees, the Ramsay Trust advisory panel, the Royal Society Newton Fund Fellowship selection committee and the Radcliffe/Harvard Fellowship committee; Mansfield was president of the Chartered Institute of Ergonomics and Human Factors; Brown is treasurer of the Dielectrics and Electrostatics Institute of Physics Group and was treasurer of the British Liquid Crystal Society.