Institution: Loughborough University

Unit of Assessment: C13 Architecture, Built Environment and Planning

1. UNIT CONTEXT AND STRUCTURE, RESEARCH AND IMPACT STRATEGY

We have created a unique, inclusive and flourishing research and innovation 'ecosystem' in the School of Architecture, Building and Civil Engineering at Loughborough University. Our research delivers tangible solutions to mitigate the global effects of *climate change*, create a *zero-carbon future* and realise the UK's *Industrial Strategy* and the *UN's Sustainable Development Goals* (SDGs).

Building on our top ranking for research environment in REF2014, we have grown our academic staff base by 21% (14 new posts), invested £2.5M in new facilities, and achieved unprecedented success with external research funding and prestigious fellowships. Consistent with our strategy to develop national centres of excellence, we have secured over £8.5M of UKRI funding to establish the UK's Centre for Postdoctoral Development in Infrastructure, Cities and Energy (C-DICE) and the UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC) National Facility for Advanced Infrastructure Construction (NFAIC). These advances – and founder-member status of the £138M UKCRIC and the £60M Energy Research Accelerator (ERA) – position us at the vanguard of efforts to address complex global and national interdisciplinary challenges.

We deliver change through our £48M portfolio of leading-edge, challenge-driven research projects, with connectivity and opportunities nurtured by our vibrant cohort of international and industrial visiting professors, which has expanded our collaborative networks, influence and routes to impact. Our new programmes in Architecture and Urban Planning, with new staff appointments, bring novel underpinning research capabilities and fulfil our aspiration to become a *truly* integrated school of the built environment. We undertake research and deliver impact within – and across the interfaces between – every discipline relevant to the design, production and maintenance of the built environment (Architecture, Urban Planning, Civil and Architectural Engineering, Construction and Commercial Management and Transport Planning and Management).

The Unit (hereafter 'the School') wholly comprises the collocated and interdisciplinary *School of Architecture, Building and Civil Engineering* at Loughborough University (LU), employing (headcount) 80 academic, 29 research, 15 technical and 26 support staff. Leadership for research and impact comes from the Associate Deans for Research (ADR) and Enterprise (ADE) who sit on the School Senior Leadership Team (SLT), which the Dean chairs, alongside other senior colleagues. The ADR and ADE sit on the University Research and Enterprise Committees, respectively, chaired by the respective Pro Vice-Chancellors.

1.1 Research Themes

Global challenges have no respect for disciplinary boundaries. Our research is therefore challenge-led and problem-driven, exploiting the opportunities at, and across, disciplinary interfaces through three linked themes: ***Sustainable Built Environment***, ***Resilient Infrastructure*** and ***Digital Transformation***.

Sustainable Built Environment research is accelerating progress towards a zero emissions future. Our research to predict, measure and control internal environments and energy demand in buildings continues to transform practice, and has expanded to cover Low- and Middle-Income Countries (LMICs). New activity includes the management and control of integrated energy systems and supporting transition towards a smart grid. Designation as an RAEng Centre of Excellence for *Sustainable Building Design*, and *three* tranches of EPSRC funding for our Energy-related CDT, demonstrate clear leadership in this field.

Resilient Infrastructure research addresses the challenges of planning, designing, delivering, maintaining and operating enduring built-assets in the face of climate change and human-induced threat. It sustains our 50-year pedigree of improving the lives of diverse, marginalised communities around the world, and addresses many of the UN's SDGs. Research is conducted in five main areas: safe mobility; transport policy; structural and geotechnical infrastructure; flood risk and management; and water, sanitation and waste management. UKCRIC funding and the Water-WISER CDT reflect our leadership in this field.

Digital Transformation research formulates radical new digital approaches to the design, manufacture, delivery and operation of buildings and infrastructure, and the complementary evolution of the organisations driving the new industrial revolution. Capitalising on nascent but rapidly maturing technologies – artificial intelligence, machine learning and digital fabrication – our research weaves new paths to enable the sector to adopt and, most importantly, rapidly adapt to, new digitally-driven approaches. Our world-leading work in 3D concrete printing is an example of our leadership in digital fabrication technology. This focus has been augmented with a more expansive exploitation of data as sources of societal and commercial value, and their valorisation, to help industry actors satisfy government policy, secure commercial advantage, address global challenges and meet intergenerational need.

1.1.1 Approach to Supporting Interdisciplinary Research

Our School is innately interdisciplinary by virtue of the breadth of work it supports and the complex challenges we address. All colleagues engage in problem-led enquiry, often informed by our collaborative network. Interdisciplinary research is further stimulated by the institutional CALIBRE framework (Collective Ambition at Loughborough for Building Research Excellence), which is the research component of the University's Building Excellence strategy. The framework includes the Built Environment Beacon (Lomas leads) which recognises our pre-eminence in this field, and four Global Challenges (Changing Environments, Energy, Health and Wellbeing, Secure and Resilient Societies) in which we are deeply engaged. Cross-campus, external and international interdisciplinary activities fostered by CALIBRE include our research with: meteorologists and geographers (Xia), health care staff and clinicians (Price), material scientists (Buswell), human physiologists (Lomas, Loveday), bio-mechanists (Fleming), biological anthropologists (Smith) and economists (Bosher, Soetanto). We also ensure our applied research is founded on cutting-edge theoretical advances in areas such as fluid dynamics (e.g. work led by Keylock and Liang), organisational theory (e.g. Dainty, Thomson) and numerical methods (e.g. Palmeri, Clubley). These theorists work across all three themes.

1.2 Review of the Unit's REF2014 Objectives and Plans

In 2014, the School submitted returns to both Built Environment (C16) and Civil Engineering (B14); all of the combined research and impact objectives in those submissions have been met or exceeded.

Objective 1: Reinforce our global reputation for integrated built environment research

Working closely with our global stakeholders, significant new collaborations have built capability to address energy demand and indoor comfort, and overcome risks from flooding and slope instability, enhancing the built environment for LMIC communities. We have become a partner of choice for leading international organisations such as UC Berkeley, TU Delft, CEPT (India), and universities in Vietnam, Ghana and Kenya, as demonstrated by our significant GCRF portfolio. Furthermore, our UK influence is demonstrated by strategic relationships with HS2 and leadership of C-DICE which brought together 18 leading HEIs around addressing the net zero challenge. With the launch of our Architecture and Urban Planning programmes and recruitment of new staff, the School has new colleagues undertaking visionary research, both within their discipline – such as architectural history – and across discipline boundaries such as in urban design.

Objective 2: Provide bespoke support for colleagues to enhance research quality
Championing the University's 'Raising Standards and Aspirations' theme, the School has developed bespoke, inclusive staff support mechanisms, such as paper and proposal peer reviews, enabling colleagues to target and win prestigious grants. Our success is illustrated by the growth in externally-funded fellowships, from 1 to 5 in this period (Afolabi, Buswell, Howard, Keylock, Smith).

Objective 3: Expand capacity and capability across resilient infrastructure research
Through the University's Building Excellence strategy, we received transformational investment of ten Excellence100 appointments in Resilient Infrastructure. One of these (Cavalaro) led the bid for a £1.3M investment in specialist equipment/facilities (NFAIC). Collectively these new staff have led and won over £4M in research grants. Intrinsic advocacy for CALIBRE's 'Secure and Resilient Society' global challenge has coalesced diverse University expertise, expanded networks (evidenced by co-authored publications) and funded research across the theme.

Objective 4: Create a new centre unifying research and enterprise from the School's two UoAs
The launch of our UKCRIC NFIAC and the award of the C-DICE postdoctoral training centre has crystallised a network of eighteen leading UK research institutions and attracted £8.5M of external funding. Having established the UKCRIC centre, we negotiated a position as the interface between HS2 and the UK research community, providing future collaborative research opportunities and effective impact pathways for our UKCRIC partners. Importantly, these investments draw upon expertise from across the School, showcasing the collective capability of the integrated nature of our research ecosystem.

Objective 5: Maximise impact by developing more effective impact pathways and exploiting commercial opportunities
Growth of partnerships with leading industry figures across multiple sectors has shaped our distinctive research and enterprise strategy. We now deliver research programmes in partnership with those delivering transformational infrastructure programmes, both in the UK and internationally. This is exemplified by partnerships with Thames Tideway, HS2, Network Rail, Highways England the National Water and Sewerage Corporation and WaterAid (Uganda), as well as with innovative SMEs, such as Alcuris and Simble, where we expedite the introduction of disruptive technologies and market approaches.

1.3 Realising Impact from Research

Our strategy for maximising the impact of our research, which embraces the whole school and every career stage, is concomitant with the institution-wide enterprise culture. Impact and its importance is embraced at senior management level and embedded across the School, as exemplified by: recognition in staff contracts and Performance and Development Reviews (PDRs); holistic enterprise training (including the Medici programme); and bespoke support to all staff, including post-doctoral researchers, from a dedicated Partnership Development Manager (PDM).

Our Enterprise Committee develops and implements the School's enterprise policy and communicates funding and partnering opportunities. Monthly clinics support staff with external partner engagement, developing impact pathways, financing and collaboration arrangements.

Partnerships lie at the heart of our approach to impact, knowledge co-production and innovation. Our strategic engagement framework exposes partners to the full range of opportunities, from UG sponsorship/placements to long-term research collaborations, consultancy and KTPs. Example outcomes include six KTPs, an Innovate UK award of £1M follow-on funding (CAVIAR2, Galliford Try), and successional industry funding (e.g. Mitsubishi project, then two studentships, £375k). Other significant partners include Highways England, Severn Trent, DHSC/NHS, BEIS, MHCLG, the Home Office, Network Rail, HS2, Thames Tideway, the

National Trust and the British Standards Institution, some underpinning specific Impact Case Studies. Such partnerships generate additional income to support future research, continued buy-in, guidance on research directions and translational pathways into organisations.

Our approach to realising impact from our research can be demonstrated by external investments in early-stage innovations to support commercialisation, e.g.: Home Office/DfT funding has fast tracked development of a portable scanner to detect concealed knives, and a novel energy-saving water-filled glass system is being considered for commercialisation by the NSG Group. Our impact case studies illustrate how BEIS funding has helped effect change in UK Government policy regarding overheating in dwellings, and a Strategic Priorities Fund (SPF) award assisted the development of 'Slope ALARMS' to enhance community resilience to landslides in Myanmar and Malaysia.

We also target competitively awarded funding to support TRL scale transition. In this REF period, fifteen colleagues accessed £840k of Higher Education Innovation Fund (HEIF) and EPSRC Impact Acceleration Account (IAA) funding to enable the transition of research into industry. This supported three Impact Case Studies, notably funding to build a dementia-friendly demonstration house in collaboration with the BRE and healthcare professionals.

We have also initiated a start-up company (Concrenetics) and registered two patents: Freeform Construction, assigned to Concrenetics to pursue commercialisation in Europe, and a new reinforced concrete building system, assigned to SolidSpace. These complement established spin-outs and licences, such as Adept Management Ltd, which has been proffering cutting-edge design management approaches since 2001.

Consultancy work provides an impact pathway by which staff expertise brings wider commercial benefit. Managed through Loughborough University Enterprise Ltd, the income from such work is reinvested in our research environment, enabling us to bridge RAs between contracts, purchase new equipment and provide training opportunities. In this REF period, 30 School staff provided consultancy advice to 82 clients yielding £3M of income, including a ≈£1M BEIS contract.

As testimony to our research impact excellence, 'Map Matching Algorithms' (Quddus) won the 2019 Enterprise Awards 'Best Impact Award', receiving 73% of the 5,000 global public votes. Our partner, Highways England, adopted our research to revolutionise their road safety interventions and continues to collaborate, funding three doctoral studentships.

Our reputation for significant research has led to impactful appointments: a COVID response project to reduce transmission in buildings with DCMS (Cook); membership of DoH advisory bodies - Estates and Facilities Productivity Think Tank, Dementia Friendly Environment Working Group, Estates and Facilities Division Advisory Group (Price); and early lessons for a new normal post COVID-19 in construction (Gibb and Chow). These appointments, founded on excellence, save and enrich lives and support wider societal goals.

Impact Case Studies (ICS)
The approach described above is captured in a rigorous, recurring multi-point impact audit, covering research theme, impact type, significance, reach, strategy, timing, evidence, and support requirements, to which all academics contribute. The six ICSs, coincidentally two from each research theme, were subject to this audit and they evidence how our culture of enterprise has delivered impact nationally and internationally.

- Sustainable Built Environment:
  - Summertime Overheating built on substantial new primary datasets gathered in BuildTEDDI projects (REF5b §3.3) and realised through collaboration with BEIS/MHCLG and support from SPF monies.

- National and European Daylighting Standards was underpinned by projects (£176k) led by Mardaljevic: Climate Based Daylight Modelling (EPSRC/Arup); Weather for Daylight Modelling (CIBSE) and propagated by accepted standardisation in the sector.

- Resilient Infrastructure:
  - Low-cost early landslide warning system tackled a hazard that kills thousands globally each year. Smith and Dixon pioneered and commercialised sensing technology that can detect soil movement, using £129k EPSRC IAA funds (initial IP protection, proof of concept field trials and licencing) alongside external investment).
  - Improving and Protecting the UK Government's largest asset – the Strategic Road Network has generated 99% accurate road collision data, transforming Highways England's approach to road safety management, illustrating our partnership approach to co-creating impact).
- Digital transformation:
  - Transforming industry understanding and practice of designing out waste through the development of British Standards on material efficiency led to publication of BS8895, with School support for development of this important British Standard.
  - Transforming the £83bn NHS built estate to deliver safe and dementia-friendly care used Strategic Asset Management (SAM) to better design, fund and manage NHS England's estate, and was achieved through EPSRC IAA funding and significant engagement with practitioners and policymakers.

1.4 Five Year Research and Impact Objectives/Plans

How the built environment evolves over the next 50 years will define humanity. Climate change, the UN SDGs and our national initiatives, as reiterated recently in the Government's *Ten Point Plan for a Green Industrial Revolution,* will frame our research. As one of very few Schools that unify all relevant disciplines and stakeholders in a genuinely interdisciplinary way, we can rise to these challenges. We predict that international collaboration, shorter impact pathways, and recruitment of the best staff will be the keys to success. Within this framework, and through consultation with colleagues and stakeholders, we have co-created objectives spanning our three core themes and beyond:

1. Building on recent success and leadership of international projects, including ten funded through the Global Challenges Research Fund (GCRF), we will continue to grow our **international reputation and collaborative research**, building on burgeoning research partnerships in China, India, USA, Singapore Greece and Switzerland, including Chongqing University, IIT Delhi, UC Berkeley, and MIT.
2. The *Build Back Better* agenda promise a stronger, fairer economy, but the full impact of COVID on these outcomes is yet to be evinced. We will work agilely to **accelerate progress towards a zero-carbon future**, as part of our Sustainable Built Environment theme. Linked to this will be building research capability around **well-being and the environment**.
3. Although Architecture and Urban Planning are new programmes, appointing research leaders in their fields will enable us to **grow our Architectural research**. We expect research in urbanism and urban design, low carbon design and digital fabrication to emerge under our Sustainable Built Environment theme.
4. Responding to conspicuous climate change and exacerbated human-induced threats, our Resilient Infrastructure research will work to **understand and mitigate flood risk** for vulnerable communities around the world. Capitalising on the UKCRIC NFAIC, we will **expand industry-academia collaboration**, with our RAEng Visiting Professor Caroline Field, as a conduit to tangible impact.
5. Within our Digital Transformation theme, we will extend our world-leading **concrete printing capability** and, with new production techniques and expanded stakeholder network, we will seek to deploy novel concrete components in significant built projects.
6. Responding to increasingly rapid urbanisation, and a heightened need for safe and sustainable living, we plan to coalesce multi-disciplinary teams from all three themes to establish a **Built Environment Futures Lab** for testing and demonstration. Alongside this,

we will embed stakeholder engagement into the life of the School by establishing a *Built Environment Futures Colloquium*.

7. Capitalising on our unique transdisciplinary capability across our three themes, we are working towards creating a **net zero-carbon facility** with **regional partners** including the East Midlands Development Corporation which is being formed around three key sites in the East Midlands: East Midlands Airport, Toton (HS2) and Ratcliffe Power Station.
8. As part of our Equality, Diversity and Inclusion (ED&I) strategy and building on our outstanding success in securing fellowships, we will continue to develop **a diverse staff profile**, particularly supporting those from underrepresented groups. We will provide development opportunities for all staff and support them towards senior roles thereby contributing to the future health of Built Environment research in the UK.

Looking to the future, the growth of the University Science and Enterprise Park (REF5a§1.1) will attract companies seeking our research and innovation capabilities. We are currently pursuing opportunities to embed our sustainable building design research into new developments to form living laboratories on this site.

1.5 Open Research Environment

The University has been a pioneer of the 'Open Agenda', actively supporting Repositories for text-based outputs (since 2005) and data (since 2015). All, 100%, of the School's REF outputs were accessible within three months of acceptance, exceeding the REF2021 requirement. In line with Loughborough's landmark Open Research Position Statement, 100% of our primary research outputs since 2020 are available on Open Access. Increasing the visibility of our outputs is regarded as key to ensuring the impact of our high-quality research.

Our School advocates using the Research Repository for open access to large EPSRC-funded datasets: the REFIT and LEEDR projects released comprehensive open datasets, resulting in over 3,000 downloads; and Firth and Hassan received a CALIBRE award their innovative Open Data approach. The School provides Open Methods and Open Software through the repository to enhance reproducibility, and our category on 'Built Environment and Design' has received 5 million downloads over the REF period.

1.6 Culture of Research integrity

Our culture of research integrity is firmly rooted within the University's Ethical Policy Framework. Our researchers are accountable for adherence to this Framework, and responsible for conducting ethics checks on all proposed projects and seeking necessary approvals from institutional Ethics sub-committees (human participants, human tissue) or the main Ethics Committee (philanthropic funding, military applications, animal testing, etc.).

The Dean appoints an academic colleague to operate our local process, review ethical approvals and liaise with Research and Enterprise Office staff and institutional committees. Our School Operations Manager is our Data Coordinator and provides advice and support on GDPR and related issues, acting as a conduit to the University Data Governance Manager for more complex queries. Our Health, Safety and Environment (HS&E) Officer, together with two deputies, ensures we always exceed the legal and institutional requirements for HS&E.

2. PEOPLE

2.1 Staffing and Recruitment Strategy

All academic staff contribute to teaching, research and enterprise activities. All academics have **ringfenced time for research and impact** activities, with specific allocations for managing research grants, doctoral supervision, impact and enterprise projects; and collaboration-building.

We expect and incentivise collegiality from the earliest career stages and, as careers develop, we expect broader leadership contributions. For example, since 2015, 12 School staff have served on the University Senate, and the School's membership has changed from 100% male to 40% female. Academic staff have open-ended contracts, while research staff are on fixed-term contracts related to projects (81 recruited since 2016) in line with sector norms. Part-time working is welcome and three academic staff work part-time.

Since REF2014, the University approach to recruiting excellent staff at all career stages, from postdoctoral and early career researchers (ECRs) through mid-career and senior roles, has radically changed, driven by the University Strategy and beginning with the 'Excellence100' campaign in which we recruited 18 world-leading staff who have already contributed significantly by securing funding, expanding our global academic and industrial links, mentoring colleagues, and enhancing teaching excellence. A special Excellence100 element, now retained indefinitely, is the **Doctoral Prize Fellowships**. The School has hosted 2 Fellows, one current and one (Smith) who subsequently secured an EPSRC fellowship and Philip Leverhulme Prize.

Building on Excellence100, recruitment to established posts is now conducted through biannual recruitment rounds, managed centrally but with significant School input, rather than piecemeal replacement hires. With excellence as the primary criterion, these rounds deliver better international recruitment and improved diversity. In total, we have expanded our staff base by 21%, while also recruiting replacements for 25 leavers, strengthening alignment of expertise with research themes and forming a truly integrated school of the built environment. For Architecture alone, we recruited 12 staff. Since 2016 we made appointments at all levels (3 Prof / Reader, 6 SL, 25 L) to ensure critical mass and leadership in the research themes. Of these 34 new appointments, 38% were female and 38% BAME. We doubled the proportion of female colleagues.

The School continually assesses its **succession** needs for research leadership positions, recently launching a new strategy enabling all colleagues to apply for such positions or join the School SLT. Two new SLT roles were introduced: Director of Academic Staffing and Development (including workload planning and resource management) and a strategic Director of ED&I.

2.2 Staff Development Strategy

Through perspicacious leadership, the School fosters an environment in which established and early-career researchers can rapidly develop to realise their full potential in a world-class research environment. We **celebrate success** with our annual School Awards, which recognise all job families and career stages, and via articles in our regular School Newsletter.

Loughborough's Organisational Development offers a wide spectrum of training opportunities and support for staff at all career stages. Courses range from earliest stages (Welcome to Loughborough) through essential training (Information security training, Unconscious Bias) to training for staff becoming senior managers (Coaching conversations for managers, Recruitment and selection). A new voluntary **mentoring programme** (launched 2020) is available for *all* staff, independent of any management structure. Mentors receive workload recognition and training.

All academics are expected to obtain **Fellowship of the Higher Education Academy** (HEA). For new lecturers, this is integral to their dedicated development programme. More experienced colleagues are supported through our `Recognition of Experienced Practitioners' scheme which requires preparation of a dossier of evidence to support their application.

Following the principles of the *Concordat to Support the Career Development of Researchers,* the University provides structured **support to postdoctoral researchers** for career progression and development, including preparation of applications for funding. We actively encourage our research staff to be part of our research culture by arranging activities tailored specifically to

their needs, such as lunchtime academic updates (e.g., REF); visiting academics' seminars; writeshops led by a journal editor; reading groups; Brown Bag lunch skills sessions; one-to-one support from our Research Development Manager (appropriate funding, Fellowships). Our development ethos has resulted in 11 academic appointments from former doctoral and postdoctoral researchers. Rapid progression of two such colleagues (PhD/RA to Senior Lecturer within 8 years) evidences the effectiveness of the support we provide.

Under the **New Lecturers' Programme (NLP)**, all new lecturers are guided by an experienced and trained academic colleague from the School who acts as Adviser. NLP (formerly academic probation) was substantially revised in 2017 and includes the full spectrum of research and impact activity (publication, funding applications, collaboration, public engagement, non-academic partnerships). New lecturers have a reduced workload in teaching and administration (33, 50 and 67% of departmental norms in consecutive years), which enables the establishment of a full academic profile in research, teaching and impact at a manageable pace. In addition to an extensive training programme leading to FHEA, the New Lecturer meets four times annually with their Adviser though many more informal meetings are the norm. New Lecturers are allocated a University-funded PhD studentship within their first two years, for co-supervision with an experienced colleague. Supervision is a requirement to pass the programme, alongside a minimum expectation on research output production, and the submission of at least one substantial grant application. Our Research Development Manager evaluates support requirements for developing first grant applications. Start-up funds are available for conferences and networking. During the assessment period, 23 School staff competed NLP and 6 have subsequently been promoted. 14 School staff are currently completing NLP.

2.2.1 Performance and Development Review (PDR), reward and promotion
All post-probationary staff have an annual PDR. This University scheme was totally updated in 2017. A supportive one-to-one discussion between the reviewee and a trained reviewer reflects on achievements over the past year and agrees objectives across the full range of activities including CALIBRE-aligned goals for research and impact activity. New PDR is a transparent way to recognise performance exceeding expectations with additional financial **reward**, overseen by a Senior Review Group. In 2019, 97% of staff met or exceeded expectations; 11% of female and 8% of male academics received financial rewards. The new scheme has particularly benefitted our research staff for whom a rigorous developmental discussion was previously sporadic and consideration for reward a rarity.

The SLT routinely encourages colleagues to apply for promotion and PDR also identifies potential candidates. In 2016, the University revised the criteria for **academic promotion** (Senior Lecturer and Reader / Professor), to ensure that the research components align with the University Strategy and CALIBRE. Evidence for cases can be based on research, teaching, enterprise (impact) or any combination to encourage balanced portfolios of work. Promotion panels take into account statements from applicants describing how personal circumstances, such as caring responsibilities, may have affected their profile. Since REF2014, 28 colleagues have been promoted, 33% identifying as female; the School now has 29 colleagues at Professor/Reader level.

2.2.2 Research and Impact Leave
Leave is available in the form of School and University Fellowships, providing up to 12 months outside regular workload to pursue agreed programmes. 4 staff (3M/1F) have secured 6-9 months of time devoted to strategic research and impact projects e.g. Dixon to deliver commercialisation and impact of the Slope ALARMS research; Price to develop an EPSRC Programme Grant; Carrillo to re-invigorate her work in 'Research 4.0' after Associate Dean terms; and Palmeri to work with international collaborators on design and maintenance of infrastructural assets.

2.3 Doctoral Researchers (DRs)

We have graduated 221 Doctoral Researchers (200FTE, 66% like-for-like growth on REF2014), including 41 jointly supervised with other Loughborough Schools. The table below shows split between traditional PhDs (82%) and 'EngD' professional doctorates (18%) for each year in the assessment period.

Type \ Year	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Total
PhDs	26.17	20.50	24.58	29.16	19.15	19.00	25.50	164.06
Prof Doctorates	5.00	4.00	8.50	5.00	6.00	6.50	1.00	36.00
Total	31.17	24.50	33.08	34.16	25.15	25.50	26.50	200.06

The 2019 **Postgraduate Research Experience Survey** reiterated the excellent support we provide as we achieved top scores across the University with overall satisfaction at 84.5% (nationally overall student satisfaction was 81%). All DRs are provided with a laptop, access to laboratory facilities, technician support, and travel and conference funds.

The School attracts **funding** to maintain its DR population (c.150 students) via University scholarships (56 since 2014), industry funding, UKRI funding, and high-quality self-funded students. The funding mix is approximately 36% internal funding, 23% from UKRI and 41% self-funders. Of these, 16% received part funding from industry.

We have an enviable **track record of running CDTs,** hosting three, with funding from UKRI and industry. Our Engineering Doctorate *Centre for Innovative and Collaborative Construction Engineering* (CICE), has trained 36 EngD students (151 since 1999), all co-funded by industry. Students spend time embedded within the company, guaranteeing impact and graduating ready for industrial R&D. The highly successful 'LoLo', *London-Loughborough EPSRC CDT in Energy Demand*, and its successor 'ERBE', *EPSRC Centre in Energy Resilience and the Built Environment*, both joint with UCL, have trained 100 PhD students since 2009, half of whom were co-funded by stakeholders. Illustrating our growth in water engineering, our latest CDT is the *EPSRC Centre for Doctoral Training in Water and Waste Infrastructure and Services Engineered for Resilience* (Water-WISER), which builds on long-standing collaborations with Leeds and Cranfield Universities. Our CDT successes illustrate the regard that students, academic collaborators, industry partners and funding bodies have for the research training environment that we have created. Further funding comes from Loughborough's EPSRC DTP (often used to match-fund), the NERC 'CENTA' DTP, University-funded mini-CDTs and a recently awarded Dunhill Medical Trust (£121k) mini-CDT across three Schools.

Our **recruitment policy** explicitly encourages applications from all backgrounds through a fair and accessible selection process. Our main annual recruitment process deploys ordered selection criteria, evaluating applicant strengths, application quality, strategic value to School and publication potential. We also consider the use of laboratory equipment and third-party funding. All applications are reviewed by a representative academic panel. The Doctoral College (DC) runs an **induction** event for new starters, complemented by School specific inductions.

Two (occasionally three) **supervisors** are allocated per student based on expertise, workload, inclusivity, and experience. Supervisory arrangements are monitored by the Director of Doctoral Programmes (DDP), with quarterly Student-Staff Liaison Committee meetings ensuring any DR-related concerns are dealt with promptly. Progress is monitored through (minimum) monthly supervisory meetings (recorded on the Co-Tutor online system) and reviewed (alongside evolving training needs) biannually by an independent assessor. During the first year of PhD studies, there is an initial 6-month review followed by annual reviews, based on a report and viva with an independent examiner, at which student **progression** is decided. Supporting DRs to submit within their funded period is a high priority. Completions are prominently celebrated in our newsletter and on information screens across the School. The overall quality of our research

degree programme is the responsibility of the ADR, with quarterly Boards considering overall cohort progression.

The Doctoral College offers over 200 **skills development** events annually, following the Vitae Researcher Development Framework requirements. This includes face-to-face workshops, the annual research conference and showcase, and the 'Café Academique' forum to debate emerging research ideas. DRs can win competitive (paid) placements in the Institute for Advanced Studies (IAS) Doctoral Leaders Programme. Further **specialist support** is available from the Mathematics Learning Support Centre, English Language Support Centre, Student Advice Centre, and the Careers Network. DRs can access wellbeing support through the DC and the School's Wellbeing Advisor (for issues such as stress, anxiety, bereavement, family or relationship issues), as well as the Employee Assistance Programme's 24/7 confidential helpline.

The School's open-plan Research Hub facilitates peer-to-peer learning between DRs from diverse backgrounds. DRs also benefit from the School's extensive seminar programme (72 visiting speakers in this REF period) and our quarterly Doctoral seminars through which students present their emerging research ideas. An active Hub Committee helps address concerns for DRs and postdoctoral researchers. We take particular pride in offering essential bespoke support – beyond mere compliance – that makes a real difference. For example, we organised and funded a travelling companion to enable a DR with cerebral palsy to undertake fieldwork in Ghana. During the COVID-19 pandemic, bi-weekly online meetings with the DDP and the ADR have ensured regular communication. One year 3 DR commented: "*My supervisors…were extremely supportive … they have been constantly in touch to make sure I am physically and mentally ok while away from home*."

The quality of our support is evidenced in a number of prestigious competitive external and internal awards, e.g. Formosa, 2018 L'Oreal-UNESCO award for women in science and the winner of the 2018 Regional Falling Walls Lab; McCarthy, the 2017 Ailsa McKay travel grant; del Pinto, selection for the 2019 UNESCO International training course and the 2019 Ede and Ravenscroft Prize; the Brembilla, 2016 Young Lighter competition finalist; and the Loughborough 2018 'Contribution to Knowledge' Postgraduate Award.

2.4 Equality, Diversity and Inclusion (ED&I)

In line with the University's 'Building Excellence' Strategy, mainstreaming ED&I has been fundamental to the School's vitality, sustainability and success, and resulted in significant enhancements:

- SLT decision-making is now informed by quarterly research activity reports with data analysed by protected characteristics e.g. funding applications and awards, PhD completions. One recent indicator of success was seen in 18/19 grant applications: 50% of applications had female PIs.
- SLT reviews workload by gender within and across grades and job families to ensure fairness.
- All academic colleagues can apply for SLT roles.
- Recognition is provided for activities that encourage underrepresented groups into engineering and STEM subjects, e.g. participation in International Women's Day and outreach programmes.
- All School committees are representative, with members from various job families (also students), career stages, and diverse backgrounds.
- The School received an *Athena SWAN Bronze Award* in 2017 –renewal currently under consideration.
- Female staff (mid-career) are supported to join the Aurora Leadership Programme (Chmutina, Chow, and Ruikar attended in the last three years).

Within the School, the Director of ED&I (Chmutina) coordinates activities, chairs the ED&I

Committee (EDIC), leads Athena SWAN planning and is a member of SLT. EDIC, which meets quarterly, has representation from all job families and the student population. It implements strategies to ensure that staff and students with protected characteristics are fully supported, develops inclusive communication strategies, and celebrates our diversity and successes. Additionally, specific events are held to better understand the needs of colleagues with protected characteristics and how they can be supported (e.g. regular meetings for female colleagues to explore better support for their career development). The School takes an **intersectional, inclusive approach** to ED&I events and training, with all staff now completing mandatory Respecting Diversity and Unconscious Bias training.

Our commitment to ED&I is mirrored in our **recruitment strategy**. The proportion of shortlisted candidates identifying as female far exceeds the proportion amongst our existing staff; since 2016, 8% of female applicants were offered a job (5% male); the proportion of female lecturers has increased from 14% in 2014 to 40% in 2019, providing the foundation for a higher proportion of women in senior positions in coming years. The proportion of BAME appointments has also increased from 16% in 2014 to 21% in 2019.

Flexible and remote working is supported, subject to agreement with the Dean, to promote and support wellbeing. Remote working is facilitated via the VPN (with secure multifactor authentication) that provides access to all University online resources. Our supporting infrastructure has eased the transition to effective home working during the COVID-19 pandemic.

Colleagues preparing for **maternity or adoption leave** are supported to attend classes and appointments. We undertake risk assessments for pregnant women, particularly if they work in the labs or in other hazardous environments, and involve our occupational health team if adjustments might prove beneficial. University funding is available to cover colleagues taking family leave, and those on leave can take up to ten *Keeping-in-Touch days* to attend meetings or important events during their leave. Towards the end of their leave, staff meet the Dean to discuss a flexible return to work where required and, whenever possible, workloads are reduced for returners during the first 12 months.

The School recently introduced a '**Carer Grant**' which contributes towards any additional caring costs, enabling colleagues to undertake professional development activities. Fourteen of our colleagues have trained to become certified **mental health first aiders** to signpost relevant services. The **Wellbeing Advisor** provides support to staff and research students. The **University Counselling Service** is available for emergency meetings and long-term treatment. The University also subscribes to the **Employee Assistance Programme** providing 24-hour telephone counselling and repeated sessions for staff with complex issues.

2.5 Equality and Diversity in REF Submission

The University Research Committee created **the REF Code of Practice (CoP) Working Group** in October 2018 with diverse membership, which included Cook from our School. All submission preparations were conducted in accordance with the CoP and subject to Equality Impact Assessments. Our School **REF committee and working groups** comprised 9 members (2 female): the Associate Dean for Research (responsible for research strategy), the Dean, two previous and current panel members, our Director of Academic Staffing and Development, our Director of ED&I, the Associate Dean for Enterprise (responsible for enterprise strategy and impact), the Research Development Manager, and the Partnership Development Manager. All members underwent REF-specific Equality and Diversity training.

All School academics contributed to the **peer review of outputs**, which led to our final submission, ensuring maximum diversity and inclusion. Output quality assessment was already firmly embedded within the School before REF2021 preparations began. Our outputs selection and assessment processes were fully in line with Loughborough's Responsible Metrics Policy.

To ensure **fair, consistent and transparent selection**, we identified outputs that convey the most original, significant and rigorous work produced by the School's current or former staff. Our School submission was subject to Equality Impact Assessments, considering gender, maternity leave, ethnicity and ECR status, which revealed no bias.

3. INCOME, INFRASTRUCTURE AND FACILITIES

3.1 Research Funding and Strategies

Holding significant research funding is the only way we can deliver solutions to the national and international challenges that drive our research. We target a variety of sources and have an exceptional record of winning competitive peer-reviewed funding. This is attributable to comprehensive support for developing proposals, including costing, developing industry links to facilitate application and exploitation, internal peer review, support for responses to reviewers, and mock interview panels. As part of the mainstreaming of ED&I throughout the School, the Director of ED&I acts on specific personal challenges to pursuit of funding (e.g. caring responsibilities). In line with strategy objective 2 (*Provide bespoke support for colleagues to enhance research quality*), we are currently developing a programme of short-term study leave (up to 1 month) for such colleagues.

Our **£48.0M portfolio comprised 275+ projects active over the REF period**: Research Councils 63%, UK Government 10%, Stakeholders (industry, charities) 18% and Others (inc. EU and overseas) 9%. This consists of: £27.9M for projects; £14.9M for doctoral training centres (CICE £5.8M, Lo-Lo/ERBE £7.7M and Water-WISER £1.4M); £1.9M other support for doctoral training including industry sponsorship; £840k for impact acceleration activities; and £2.5M for specialist equipment and estates upgrade.

An **additional £3.6M** of funding has already been awarded for projects starting between Aug-2020 and Dec-2020. These new awards, combined with notable recent successes (e.g. our two CDTs, the *UKCRIC* National Facility for Advanced Infrastructure Construction and the UK Centre for Postdoctoral Development in Infrastructure, Cities and Energy*),* underpin our plans for the next 5 years (REF5b§1.4). The strategic importance of our grant portfolio to our ambitions under the three research themes is set out below. We emphasise major and prestigious awards, the importance of research consortia to our portfolio, and grants that have led to the impacts selected as ICSs.

Sustainable Built Environment
Our research on energy demand in dwellings attracts funding from the UKRI (EPSRC and Innovate UK), Government (BEIS), EU and industry partners to deliver a **£4.36M** portfolio of projects including:

- *Low Effort Energy Demand Reduction* and *Methods and Metrics for Moisture Risk Assessment*.
- The UK's largest concentration of EPSRC *Transforming Energy Demand through Digital Innovation (TEDDI)* projects: *DEFACTO*, *Digital Energy Feedback and Control Technology Optimisation; Hot Water Provision in Homes, Consumption, Storage and Lifestyle*; *REFIT, Personalised Retrofit Decision Support Tools for UK Homes using Smart Home Technology.*
- Leadership of the *TEDDINet* network.

Primary data sets gathered in these projects enabled research into summertime overheating in homes and the subsequent impact (ICS REF§5b1.3). Projects in support of policy initiatives to reduce domestic energy demand are supported by government and include *Technical Evaluation of SMETER Technologies* and *Demonstration of Energy Efficiency Potential*. Our longstanding research into the quality of the internal environment and daylight led to new Daylight Standards (ICS REF§5b1.3).

Our strategy is also advanced by **£1.68M** of research projects on management and control of energy in buildings using digital technology. Howard (Excellence100 appointment) has given

impetus to this research by securing an EPSRC Innovation Fellowship to work full time on *FlexTECC: Flexible Timing of Energy Consumption in Communities*. This complements other energy management and flexibility research: *SCENe, Smart Community Energy Network* (Innovate UK) and *Energy-efficient buildings flexibly connected* (EU), *Design4Energy* (EU).

We have used our enhanced research base to progress new activity into comfort and internal environments in Low- and Middle-Income Countries (LMICs), funded by **£690k** from the UKRI GCRF, British Council and British Academy. The lives of some of the world's most marginalised peoples will be enhanced by projects into: *Low Energy Cooling and Ventilation for Indian Residences (LECaVIR); Reducing Global Energy Use in Buildings while Improving Occupant Comfort and Well-being*; and *Low Carbon Climate-responsive Heating and Cooling of Cities.*

Our recognised experts in building energy and the internal environment received **£2.44M** prestigious stakeholder funding to address industry challenges. Examples include working with Kingfisher PLC, owners of DIY stores across the world (e.g. B&Q), to develop *New Energy Efficient Products,* and with Mitsubishi to enhance *Energy Management of Heat Pumps in Europe* and to improve *Indoor Environmental Quality by Leveraging Advanced IEQ* systems*.*

Funding supported two ICSs: summertime overheating used data sets from BuildTEDDI projects and daylighting standards built on projects funded by EPSRC, Arup and CIBSE (ICS, REF5b§1.3).

Resilient Infrastructure

Of strategic importance is our UKCRIC founder member status (BEIS, £138M, Thorpe leads at Loughborough) and associated activities. Working with a **consortium** of UK Universities, including UKCRIC partners, and stakeholders (20+), we research deterioration of geotechnical infrastructure in a changing climate, with funding of **£1.26M**. We lead one of three challenges in the *EPSRC Programme Grant - Assessment, Costing and Enhancement of Long Life, Long Linear Asset (ACHILLES)*, and were instrumental in delivering its predecessor - *Infrastructure Slopes Sustainable Management and Resilience Assessment (iSMART)*. Outputs are influencing design (HS2) and the operation of linear assets (e.g. Network Rail). Complementary research to develop new sensors to monitor landslides and buried infrastructure is advanced through Smith's EPSRC Fellowship, his Leverhulme Prize and EPSRC IAA funding, leading to impact on slope monitoring (ICS REF5b§1.3).

Our Engineering Doctorate Centre (CICE) is an important driver for research on resilience of structural and geotechnical systems. Industry co-funds and co-creates many of our doctoral projects. Working across the School's discipline boundaries, EPSRC First Grants, Innovate KTPs and industry funding, totalling **£920k**, have allowed us to address a range of industry challenges, including: modelling and design practice for structural systems; advanced construction methods in modular housing; asset condition evaluation for corrosion damage; maintenance management of drainage systems; performance of rail track; durability of materials; sustainability of materials and designs; earthworks deterioration; and blast response of structures.

Research on safe mobility has produced impact (ICS, REF5b§1.3) and attracted **£780k** of funding from the EPSRC and stakeholders (Highways England), for projects including: *Social Level Impacts of Connected Autonomous Vehicles*; *Estimation of a Risk Profile to Operatives and the Public from Motorway Hard Shoulder Incursions*; and *Assessing the impact of Intelligent Mobility on Traffic Performance*. Wider transport policy and practice is informed though **£370k** of research on travel planning and parking behaviour, including: *Using Novel sensing Techniques to Enhance Rail Services*; *Collaborative Highway Engineering to provide Optimisation and Best Value*; and *Virgin Park and Charge.* These projects engage our urban planning and transport disciplines.

Our strategy in response to international need has been to expand flood risk and management research, achieved through the Excellence100 appointments of Liang and Xia. Interdisciplinary projects funded by NERC (including GCRF), EPSRC and the UK Met Office total **£2.19M** and include:

- *Flood Prediction using Real-time Sensing*;
- *FUTURE-DRAINAGE: Ensemble Climate Change Rainfall Estimates for Sustainable Drainage*;
- *Web-Based Natural Dam-Burst Flood Hazard Assessment and Forecasting System*;
- *Impact Scenario Modelling for Risk-based Flood Warning in India*;
- *Valuing the Benefits of Blue/green Infrastructure for Flood Resilience…. in Vietnam*;
- *Living Deltas Hub*.

We also research disaster risk management, resilience and security of the built environment via **£540k** funding, such as the EU projects, *Designing Safer Urban Spaces* and *Evolving Concepts of Security*.

For nearly 50 years our Water Engineering and Development Centre (WEDC) has researched sanitation and waste management to improve lives in LMICs. This has been sustained with **£3.96M** project funding from the EPSRC, ESRC, The Bill & Melinda Gates Foundation and DFID. Projects include: *Reinventing the toilet*; *Promotion of Faecal Waste Flow Diagrams*; and *Building Innovative Delivery Systems for Water, Sanitation and Energy in Urban Africa.* Our funding from DFID acknowledges our expertise in water, sanitation and hygiene in South Asia. WEDC are partners in a new Centre addressing climate, resilience, energy and environment, hosted by the School of Social Sciences and Humanities and underpinned by a significant (£35M) grant.

A **£1.13M** group of projects on energy from waste, addresses energy poverty, health and waste management, and includes an RAEng Development Research Fellowship to Afolabi for *Advanced Technological Synergy for Renewable Energy Production in sub-Saharan Africa.* This builds on British Council funding for *Community Scale, Decentralised Anaerobic Digestion for Energy ……* and *Technical Integration of Sustainable Energy and Water*, plus EPSRC-funded *Rural Hybrid Energy Enterprise Systems,* among others.

Digital Transformation

Our digital manufacturing research on 3D concrete printing (3DCP), a technology invented at Loughborough, has shaped the international research landscape for large-scale additive manufacturing for construction. This research has been advanced with Buswell's UKRI 'Research Leadership' award via the Industrial Strategy Challenge Fund (**£1.13M**) and EPSRC and Innovate UK projects of **£1.15M**: *CAMBER - Concrete Additive Manufacturing for the Built Environment using Robotics*; *Developing an Industrial 3DCP cell*; *Design-for-manufacture of 3D Concrete Printed Structural Composites; MMC, Digital and Whole-life Performance*; and *Manufacturing Integrated Building Components using Digital Hybrid Concrete Printing Technology.* Impact includes a start-up company, Concrenetics, to embed the technology into the concrete precast industry.

Working at the confluence of architecture, management and building energy, our digital practices research has focussed on three-dimensional representation of the built environment. EPSRC funding of **£1.53M**, including 'Transforming Construction' funds, has delivered:

- *Digital Enablers for Construction Transformation*;
- *'Thinking Inside the Box': A Mixed Reality Development Platform for Co-creating Energy Efficient Retail Spaces*;
- *The Bicester Eco-town Process Improvement Toolkit*;
- *The Dementia House*;
- *Enabling Real-time Digital Fabrication Methods for Co-production*.

Royal Society and HEIF funds support work on Building Information Modelling (BIM) technologies, and Gibb's Chair in *Complex Project Management* was funded by the RAEng.

Construction safety research continues to have impact. The Institution of Occupational Safety and Health funded projects totalling **£890k** include: *Nanotechnology – Implications for Construction*; *Management of OSH in Networked Systems of Production or Service Delivery*; *SME & Micro Organisations' Engagement with Occupational Safety & Health*; and *Learning from Longitudinal Research on Large, Complex Multi-Site Construction* – the latter in partnership with Thames Tideway Tunnel. Further impact stems from our long-standing Healthcare facilities research (ICS REF5b§1.3), assisted by an EPSRC IAA *Activity Acuity Adaptability Flow Emergency Departments* project.

Waste management research has been propelled by EU and EPSRC projects totalling **£1.21M**, culminating in our core involvement in the forthcoming £4M EPSRC *Interdisciplinary Circular Economy Centre for Mineral-based Construction Materials*. The EU projects, *Activating Circular Services,* and *ICEBERG*: *Innovative Circular Economy Based Solutions,* will create BIM tools and enable digital tracing of materials. In concert with the EPSRC *Creative Outreach for Resource Efficiency* project, these have led to promulgation of the techniques throughout the academy, generating measurable impact on practice (ICS REF5b§1.3).

3.2 Organisational and Operational Infrastructure Supporting Research and Impact

The Research and Enterprise Office (REO) supports our research and impact ambitions with a team of 20 staff who alert School staff to funding opportunities, guide staff developing funding applications, support costing, develop collaboration agreements, protect IP and know-how, and provides legal advice. Our School has a dedicated Research Development Manager (RDM), and a Partnership Development Manager. A specialist Fellowship Development Manager in the REO works closely with the School RDM to support Fellowship applicants, who are also mentored by existing Fellows. Rigorous proposal peer review and interview preparation have resulted in five Fellowship successes.

Laboratory and field activities are supported by a team of 14 highly skilled technical staff to design, build and operate research facilities. The quality of this support is exemplified by Darwin, who was Highly Commended in the national Papin Awards 2019, which recognise and excellence among Technicians in Higher Education.

Delivering our strategy requires continued vigilance to identify emerging global research challenges and funding opportunities. Senior staff, in particular, are expected and supported to take external leadership roles and collaborate with the very best academic groups, bringing back insights that can be shared with colleagues. Loughborough's Institute of Advanced Studies assists with our engagements with world-leading academics and the School has taken a leading role in its programmes on 'Water' and 'Nation'.

An important facet of our strategy has been developing a new **research cluster** in advanced infrastructure construction, linking our established work on novel infrastructure materials and techniques with opportunities emerging from *Digital Transformation* research. The Excellence100 appointments of Cavalaro and Blanco, coupled with award of Buswell's Fellowship, led directly to our securing of the UKCRIC National Facility for Advanced Infrastructure Construction (NFAIC), the award of a substantial EPSRC grant to expand our 3D concrete printing facilities, and the conception of Centre for Postdoctoral Development in Infrastructure, Cities and Energy (C-DICE). This unique combination of research expertise, advanced facilities and researcher skills development has been created to deliver outputs of the highest quality and global impact.

3.3 Physical Infrastructure and Facilities Supporting Research and Impact

Building on our REF2014 top-ranked research environment, we have continued to invest in estates and specialist equipment. Our purpose-built 3000m^2 laboratory houses the equipment, machines and test facilities needed to advance our building energy, structures, materials,

geotechnics, geomatics, visualisation, and digital fabrication research. A wide range of economic, policy and health impacts draw upon our physical infrastructure: studies for industry partners in our advanced hygrothermal performance facility, employing our pre-eminence in 3D concrete printing to establish new construction facilities, and Highways England utilising our processing/interpretation of national data sets on traffic accidents to improve road safety. Continued enhancement of our research infrastructure places us in a strong position to respond to global challenges and national initiatives.

During this REF period, we have invested **£2.5M** in our infrastructure estate and facilities, comprising £2.1M for the purchase of advanced equipment and £450k for refurbishment. Refurbishment works support our strategic decision to grow the Digital Transformation theme and, specifically, to establish architecture. Works also included refurbishment of the water tower that feeds our hydraulics flumes and flood models. Strategic investments in this REF period are as follows.

***Sustainable Built Environment*:** In support of our aim to understand and improve building performance, we have invested **£590k** in new facilities funded by EPSRC and Department of Energy & Climate Change. This includes commissioning an advanced hygrothermal performance facility for studying thermal and moisture performance of building constructions at scale; acquisition, refurbishment and instrumentation of six test houses; field monitoring equipment; and equipment for thermal comfort, particle image velocimetry and tracer gas experiments. These investments complement our existing daylighting suite, fluids laboratory (including a large brine facility for modelling buoyancy-driven natural ventilation) and thermal comfort chamber.

***Resilient Infrastructure*:** We have recently received **£1.3M**, primarily competitive EPSRC capital equipment funding, supplemented by University funding. Foremost is the EPSRC award to establish our UKCRIC *NFAIC*, which delivers:

- a full-scale, automated, flexible mould, controlled by 100 actuators;
- a 200m^2 simulator, including a high-accuracy tracking system to assess small- and large-scale construction processes;
- equipment to support work on modern methods of inspection and renovation;
- a high payload drone system with a suite of long-distance assessment tools; and
- a near-surface automated cell and rig for the autonomous repair of loaded components.

As a national facility, we encourage use of these facilities for collaborative projects with UKCRIC partners, other academic institutions and for stakeholder-funded projects.

In addition, we have purchased the following advanced equipment:

- sensors for field infrastructure health monitoring observatories;
- two robotic survey total stations;
- a high load structures testing system;
- a shear device for testing soil construction elements; and
- a remote sensing vibrometer.

This equipment is employed in our large-scale static and dynamic heavy structures testing facility and at field test sites. This investment has also funded elemental and mercury analysers for water quality evaluation, and a new GPU-based high-performance computer for hydrological flood risk modelling.

Digital Transformation: We have acquired new buildings and extended and remodelled studio and digital fabrication space, totalling 1,290m^2, in support of our strategy to embed architecture in the School. Investment of **£190k** funded upgrading the Freeform 3D concrete printing facility (e.g., space upgrade and purchase of two robotic arms), and equipping a visualisation suite. Investment in the UKCRIC facilities also benefits Digital Transformation research, integrating the new robotic cells for 3D printing and spraying (various materials), including a robotic manipulation and jet spraying cell.

Supporting all three themes, we capitalise on the University's **£3.5M** high-performance computer cluster – one of the country's fastest – deploying it for computational fluid dynamics and turbulence modelling associated with building ventilation, flood risk and infrastructure resilience research.

3.4 Specialist and Shared Research Infrastructure and Facilities

Of our specialist infrastructure and facilities, the following are unique in the UK:

- UKCRIC NFAIC
- Freeform 3D concrete printing facility
- Hygrothermal performance facility
- Family of slope sensor field test sites
- Six test houses instrumented to study occupancy/building performance.

The School is fully committed to regional and national collaborations to promote and coordinate the sharing of research facilities.

Examples where we gain value from enhanced access include: **£138M** of unique UKCRIC facilities for studies of infrastructure design and performance; national engineered slope observatories through the ACHILLES programme grant; and a host of energy-related resources and facilities across the Energy Research Accelerator consortium.

3.5 Significance of Major Benefits-in-kind

Through our extensive network of industry partners, we gain added value from access to data sets, buildings, construction projects and national infrastructure at sites that otherwise would be closed to research. Research, impact activity and outputs in all three themes are underpinned by privileged access to, for example, our use of English Housing Survey data to inform energy demand in buildings, site access to rail, road and flood structures to study deterioration, and hospital expenditure data for insights into facility design and maintenance. Although difficult to quantify, the benefits are transformational.

4. COLLABORATION AND CONTRIBUTION TO THE RESEARCH BASE, ECONOMY AND SOCIETY

4.1 Supporting Research Collaborations, Networks and Partnerships

Our multi-disciplinary work flourishes from dynamic interactions with industry partners and long-standing, stable international relationships with world-leading Universities. Collaborations with e.g. Stanford (30 years), New South Wales, Hong Kong University (>25), MIT and Georgia Technology (17) and UC Berkeley (12) have resulted in collaborative projects, such as the Global Innovation Initiative grant with UCB and CEPT (India). Our staff actively participate in collaboration-building initiatives and have co-authored over 1100 journal articles in this REF period, 40% of which are with international institutions.

A variety of mechanisms support the establishment and maintenance of collaborations, networks and partnerships. At School level, all staff have a discretionary fund, which permits travel to meet collaborators. Our RDM and senior staff support earlier career academics, who can access seed-corn funding, travel grants and guidance to initiate new collaborations. Sometimes ECRs win small, but potentially career-changing, travel grants, e.g.: Marjoribanks, GB Sasakawa Foundation, collaboration with Kyoto University; and Chmutina, Daiwa Foundation, Ritsumeikan University, Japan. At University level, the Built Environment Beacon instigates cross-campus bridges between diverse academics, with ring-fenced funds enabling pump-priming and proof-of-concept studies. The Beacon helps corral academic collaborators and industry partners, and this has been a factor in ten GCRF grants via the NERC, DFID and the British Council. Senior staff have undertaken missions to leading research universities in China, India and Singapore and ETH Zurich to expand our worldwide profile. The University's Fellowship scheme has enabled

staff to work with leading overseas academics, including TU Delft, the University of Athens, Penn State, Stanford and UC Berkeley. These initiatives, the University's visiting academics scheme, and the Institute of Advanced Studies have brought over 70 academics from 24 countries to our School in this REF cycle. They present lectures and run workshops, enriching our research environment. Together these mechanisms enable a multitude of individual collaborations as well as our active participation in, and leadership of, major networks regionally, nationally and internationally.

Regionally, the Energy Global Challenge positioned the University as a partner in the Energy Research Accelerator (ERA), a joint initiative comprising the Midlands' eight research-intensive universities (in the 'Midlands Innovation' partnership) and the British Geological Survey. ERA creates a powerful voice promoting the region's world-class energy research capability and the School led the development of its Doctoral Academy. With ERA partners from the Universities of Nottingham and Birmingham, the School (Lomas) leads the Midlands' contribution (integration of PV and heat storage technologies into active buildings) to UKRI's £36M *Active Building Centre* (10 HEIs, led by Swansea).

Nationally, we consolidated our UKCRIC founder-member status (13 HEI partners led by UCL) e.g. through *NFAIC* and *PLEXUS* (Priming Laboratory EXperiments on infrastructure and Urban Systems), stimulating inter-laboratory working across UKCRIC. The combination of our UKCRIC and ERA activities, particularly our leadership of the ERA Doctoral Academy, was the foundation for the Centre for Postdoctoral Development in Infrastructure, Cities and Energy (C-DICE), UKRI's largest ever investment in postdoctoral training. Under the School's leadership (Dainty), C-DICE unites 18 HEIs from the UKCRIC and ERA consortia working at the vanguard of infrastructure, cities and energy research in the region, supported by twelve industry and government partners.

We have initiated and now lead new multi-institution consortia, e.g. the BuildTEDDI network (22 Universities) and joined others' collaborations, e.g. the Smart Energy Research Laboratory (7 Universities) and the Future Urban Ventilation Network (11 Universities). Two of our CDTs are collaborative: WaterWiser, with Leeds and Cranfield Universities; and ERBE with UCL and the 13 Irish research institutions in the MaREI Research Centre.

Internationally, Richards' AHRC-funded DELOS Network includes academics from 33 institutions in 9 countries studying 'contemporary concerns about demographic pressures and environmental sustainability'. Colleagues internationalise their research by joining established collaborations, such as International Energy Agency (IEA) Annex 79, 'Occupant-centric building Design' and IEA Annex 71, 'Building energy performance assessment' for which we provided data from our matched-pair test houses to 50 research teams in 13 countries. Staff participate in nine EU projects collaborating with 115 partners in 28 countries; 'ICEBERG' is a €15M consortium of 35 EU partners. The School is also part of the prestigious UNITECH network of leading Engineering Universities in Europe (including Chalmers University of Technology; RWTH Aachen; and Politecnico Di Milano, amongst others) and multi-national corporate partners (including Hilti, Buhler, ABB and Evonik). This network facilitates exchanges and collaboration between students, staff members and engineering industry. Through this network, El-Hamalawi won an EU grant collaborating with INSA-Lyon and TU-Delft to deliver a pan industry/university training course for DRs to hone transferable skills gained during their PhD.

4.2 Interaction and Engagement with Research Beneficiaries

In line with strategy objective 5 (*Maximise impact by developing more effective impact pathways and exploiting commercial opportunities), w*e endeavour to build symbiotic relationships with research beneficiaries.

We have created forums that enable potential users to ensure our research addresses pressing

social, economic and technical challenges. In 2003, Thorpe co-founded COMIT (Construction, Operation & Maintenance through Innovative Technology), which today links 95 technology providers and construction organisations with Loughborough and 7 other universities. COMIT promotes effective use of IT and has developed BIM, Digital Twins and drones guidance.

The Advisory Boards of our three CDTs help shape and steer the School's doctoral research portfolio and provide contact with potential co-funding project partners. The Boards comprise over 30 diverse organisations, representing the breadth of our stakeholder community: central government (BEIS, MHCLG); health and well-being (PHE, DHSC); energy suppliers (E.ON, EDF); digital technology (Passiv Systems, Simble); construction (Cundall, Galliford Try); materials (Knauf); consultancy (Arup, AECOM); water industry (Scottish Water, Severn Trent); professional institutions (RICS, CIBSE); and charities (NEF, Age UK).

Our extensive network of collaborators work with us in a spirit of co-production to realise immediate tangible benefits. Senior stakeholders are engaged as Visiting Professors (VPs) by the School (19 since 2014), of whom Caroline Field (ARUP), David Williams (WSP) and Darren Woolf (Hoare Lea) were part-funded by the RAEng. Our knowledgeable partners co-create new research projects, provide direct (REF5b§3.1) and in-kind funding (REF5b§3.5), and provide direct routes to impact. For example, of the ten most recent UKRI projects with partners' contributions, 83 partners provided £186k of cash and in-kind contributions to the research. The in-kind contributions such as data, access and knowledge can be unique and invaluable. Since 2014, our enterprise work with stakeholders has secured income of £3M from 82 organisations. Some projects involve multiple stakeholders, for example in TEST (BEIS, £335k) we coordinated the contributions of nine energy technology companies.

The surplus from such commercial work provides unfettered funds to enable bridging of postdoctoral researchers between contracts, pump-priming of ideas, and equipment purchase. Consultancy and research with industry partners has provided a legacy of equipment and facilities. Of note are our four test houses and associated controls and monitoring equipment – purchased for our Kingfisher project (REF5b§3.1) – and our hygrothermal test facility funded by BEIS (REF5b§3.3). These facilities have since supported work by nine DRs and five postdocs.

In this REF period, around 50% of our graduated PhD and EngD students benefitted from industry co-funding. Collaborators co-supervise and host our students, and provide advice and guidance, enhancing the training experience and providing an impact pathway. In addition to co-funded CDT students, the BRE Trust funded five PhD students, and three EngD students were funded by HS2, amongst others.

4.3 Wider Contributions to the Economy and Society

Outside the selected ICSs, additional significant contributions to society, the economy and health and well-being have been made.

Nationally, our diverse and curiosity-driven research addresses some intractable and nationally-significant issues, not always in our core research areas: *Knife crime* - turning mobile phones into portable knife-detecting scanners (DSTL, El-Hamalawi); *retail sustainability* - saving TESCO >£4M pa in energy through no-cost reduction strategies (EPSRC, Dainty); *heritage preservation* - space remodelling at Ickworth House preventing art work/furnishing deterioration (National Trust, Mardaljevic); *sport* - sustainable artificial pitch maintenance (EPSRC/Innovate, Fleming); *wind farm design* (E.ON, Cook); *climate inequality* (BEIS, Lomas)*; fuel poverty* (public utilities, Loveday); *living with dementia* (EPSRC, Cook, Price, Glass).

Internationally, our world-leading energy research in LMICs has expanded substantially e.g. the REFIT (British Council) and LECaVIR (EPSRC) projects are improving indoor health in hot countries whilst our flooding and landslide research is enhancing community resilience in Myanmar and Malaysia. Perhaps our best-known international contribution is the outstanding 50-

year record of the Water Engineering and Development Centre (WEDC) and its practical fieldwork to improve the lives of marginalised people in LMICs. Underpinned by a portfolio of 16 sanitation, water supply and flooding grants (REF5b§3.1), WEDC staff have: developed monitoring and evaluation frameworks, and conducted research, for two phases of Plan International's £38M South Asia WASH Result Programme to deliver improved water and sanitation to millions of people in Bangladesh and Pakistan; assessed the institutional capacity of the Chittagong *Water Supply and Sewerage Authority, Bangladesh*; and assisted the *National Water and Sewerage Corporation of Uganda* to enhance the livelihoods of slum dwellers in Kampala. Such projects have entailed collaborations with 55 research organisations, governments, regional authorities, and international NGO's.

4.4 Engagement with Diverse Communities and Publics

Staff and DRs proactively disseminate research outcomes to reach diverse audiences.
Mainstream media: TV presentations - e.g. BBC/ITV News, Off-site housing (Goodier), flooding in the region (Bosher); BT Sport/Rugby Tonight, Artificial turf and injury (Fleming); Discovery Channel/Daily Planet, Slope stability (Dixon, Smith); CNN, Hurricanes (Chmutina); Uganda TV, Water supply (Kayaga). Radio interviews - e.g. BBC Radio4/You and Yours, Overheating (Lomas).
Social media: Tweets, Podcasts and YouTube content are created to widen interest in our research. Notably, Chmutina hosts a weekly 'Disasters: Deconstructed Podcast' (over 32,000 downloads since Jun-2019) and holds a British Academy outreach grant.
Print Media: Our research is increasingly recognised and recommunicated. Since 2014, our research has featured in the FT, Telegraph, Guardian, local media, and niche publications, e.g. 'Insurance News', 'MedicalXpress'.
Role models: Twelve staff and several DRs have enthused audiences in schools and other public settings with their research. For example: Palmeri and Lombardo established and judged the secondary school 'Tower Tech. Challenge' for the '3M Young Innovators Challenge'; architecture staff engaged pupils in two schools to design outdoor learning spaces, with one subsequently built. To captivate wider audiences our DRs regularly join the STEM Ambassadors scheme, HEFCE's National Collaborative Outreach Programme and Loughborough's annual 'Engineering Experience'. Our DRs and postdoctoral researchers' 'Bright Club' comedy nights in local hostelries were especially memorable!

4.5 Contribution to the Sustainability of the Discipline

Many staff have contributed to the development of professional guidelines and standards: Cook contributes to Part F of the English Building Regulations and ASHRAE Standard 62.1 - Ventilation (international); McLeod sat on the Building Regulations Advisory Committee working party on Overheating in Buildings; Mardaljevic was the UK principal expert developing EU CEN/TC 169 WG11 - Daylighting; Ruikar sat on the development committee for BS8644 - Management of Fire Safety Information; Austin is a member and former chair of CEN TC104/WG11 - Fibres for Concrete, as well as a Member of BSI Working Group B/517/WG10 - Sprayed Concrete; and Osmani is the panel chair of BS 8895 Parts 1 to 4 - Material Resource Efficiency in Building Projects.

Staff also contribute to advisory panels and professional associations: Gibb is a member of the industry steering group for the implementation of the Hackitt report on the Grenfell Tower disaster; Price was a member of the DoH Estates and Facilities Productivity Think Tank; Goodier gave evidence to the government committee into modern methods of construction; Osmani chairs the Construction Industry Research and Information Association (CIRIA) Sustainability Advisory Panel: Thorpe and Dainty are former chairs of the Association of Researchers in Construction Management (ARCOM), whilst Chow and Soetanto are current board members.

Given our close association with the professional institutions, the School often hosts their regional and national meetings and has been pleased to provide a venue for presentations by

incoming Institute Presidents: Stephen Lisk and John Field, CIBSE Presidents; Bjarne Olesen and Tim Wentz, ASHRAE Presidents; and Bill Bahnfleth, ASHRAE Vice President.

We host international, national and local conferences and workshops to unite academics and research users. Since 2014, colleagues have hosted nine international conferences/workshops at Loughborough, for example: Howard hosted the 5th Building Simulation and Optimization Conference of the International Building Performance and Simulation Association (IBPSA) England, which attracted 100 delegates from 15 countries; Mardaljevic the 17th International Radiance workshop, 60 delegates from 17 countries; and Richards the third DELOS workshop. WEDC organise their renowned annual conferences, the 38th (2015) and 40th (2017) which had over 400 participants, 250 from overseas, were in LU and others since 2014 were in Vietnam, Ghana and Kenya.

4.6 Indicators of Wider Influence and Recognition

In line with strategy objective 1 (*Reinforce our global reputation for integrated built environment research*), staff are encouraged to engage in external activities. Their influence and recognition are evidenced here through their work for funding bodies, at conferences, and with the leading journals, and finally by the awards they receive.

Shaping the funding landscape
Virtually all staff act as reviewers for one or more of the UKRI funding councils as well as for the Leverhulme Trust, Nuffield Foundation, British Council, Royal Society and the Wellcome Trust. Nine staff have sat on UKRI prioritisation and evaluation panels. Invitations to review for overseas research funding bodies attests to the international recognition of our staff e.g., Natural Sciences and Engineering Research Council of Canada, Hong Kong Research Grant Council, US Department of Agriculture, Netherlands Organisation for Scientific Research; Academy of Finland Natural Sciences and Engineering Research, and the European Union (Horizon 2020). Notable and influential contributions are made by Thorpe, Deputy Chair of the REF2021 UoA C13 sub-panel and a member of the Hong Kong RAE2020 Built Environment panel; Lomas, who was Deputy Convenor of the Hong Kong RAE and Buswell and Lomas who were invited to join EPSRC collaboration panels in India and China. Thorpe and Lomas were also members of the REF2014 Built Environment Panel.

Conference leadership and keynote lectures
Since 2014, staff have co-organised conferences in the USA, Italy, China and the UK and over 30 colleagues have chaired conference sessions related to our three themes, e.g.:

- *Sustainable Built Environment* – IBPSA 2017 (San Francisco) and 2019 (Rome), ASHRAE Winter Conf, 2020, and Building Simulation and Optimization, 2020 (online);
- *Resilient Infrastructure* – Smart Infrastructure and Construction, UK, 2019, Building Resilience, Portugal, 2019, International Conference on Building Resilience, 2018, Lisbon and WEDC conferences in 2016 (Ghana) and 2018 (Kenya);
- *Digital Transformation* – Construction, Operation & Maintenance through Innovation Technology, London, 2019 and ICT in Design, Newcastle, 2019.

Over 60 keynote or invited lectures have been delivered at international conferences since 2014. Keynotes include: Palaiologou, UNESCO conference, New Delhi, 2018; Goodier, International Conference on Sustainable Construction, Vietnam, 2014; Bosher, 8th (i-Rec) Conference on Post-disaster reconstruction, Toronto, 2015; Dixon, GeoAmericas Conf., Miami, 2016; Chmutina, International colloquium on nature-based solutions for water management, Mexico, 2020; Liang, Geo-disaster reduction, Chengdu, 2016; Palmeri, 1st ECCOMAS Thematic Conference on Uncertainty Quantification, 2017, Greece; Mardaljevic, New York Green Building Conf. 2017; Fleming, Sports Engineering, Rajathan, 2017; Osmani, Unlocking the potential of modern technologies, Dubai, 2018; Ruikar, Digital Transformation in UK AECO Sector, India, 2020; and Buswell, Digital Concrete, Zurich, 2018.

Journal Editorship
All colleagues referee for international peer-reviewed journals in their field. As recognition of expertise and influence in their fields, staff have edited 15 journal special issues, e.g.: Overheating in buildings: lessons from research, Building Research and Information, 2016 (Lomas); Wind energy structures, Proc. ICE Structures and Buildings, 2019 (Palmeri); and Inter-scale transfers and flow topology, Journal of Fluid Dynamics Research, 2016 (Keylock).

Most significantly, 22 staff have been appointed as editorial board members for journals across our three themes. Our recognised world-leaders are the editors, or associate editors, for leading built environment journals. Their influence ensures research integrity and shapes the international research landscape. Since 2014, staff have edited Construction Management and Economics (Dainty), Geo-environmental Disasters (Liang), Advances in Water Resources (co-Editor-in-Chief, Sander), Built Environment Project and Asset Management (Hassan) and ICE Transport Journal (Frost), and are associate or deputy editors for Water Resources Research (Keylock), Engineering, Construction and Architectural Management (Thomson), Lighting Research & Technology Journal (Mardaljevic), Science and Technology for the Built Environment (Cook), IT in Construction (Ruikar), Environmental Research and Technology (Osmani) and the Journal of Hydrology (Liang).

Awards and Fellowships
Twenty-three **'*best journal paper'* awards** have been won since 2014, including:
- Mardaljevic, Leon Gaster Award, 2016, Society of Light and Lighting.
- Gibb, Goodier & Sander, Thomas Howard Medal, 2018, Journal of Construction Materials.
- Lomas 2016 and Lomas and Allinson 2020, the CIBSE Carter Bronze Medal.
- Fleming 2016 and Dijkstra & Dixon 2014, Rees Jeffreys Award, ICE Transport;
- Palmeri, 2016, E. H. Thompson Award, Journal of the Photogrammetric Record.
- Dainty, Best Paper Award, 2015, Engineering Project Organization Journal.

Personal awards for longstanding and impactful work have been received by several staff:
- Dixon, Water Industry's '*Most Innovative New Technology of the Year'* Award (2014) for research on leak detection in plastic pipes and the '*Outstanding Innovation 2014 Award'*, for the most significant contribution to the UK water industry.
- Smith, '*ICE Merit Award'* (2015) for development of the slope alarms system and the Worshipful Company of Engineer's '*Hawley Award for Engineering Innovation'* (2015).
- Thorpe the '*William Kemp Award'* of the ICE (2016) for contributions to Civil Engineering in the East Midlands.

Staff have received five **competitively-funded Fellowships** across all three research themes:
- Buswell - Industrial Strategy Challenge Fund Transforming Construction Research Leadership Fellowship, on '*Manufacturing integrated building components using digital hybrid Concrete Printing (HCP) technology*' (2019-2021, £1.1M).
- Howard - EPSRC Innovation Fellowship entitled '*Flexible timing of energy consumption in communities'* (2018-2021, £496k).
- Smith - EPSRC Postdoctoral Fellowship, '*Listening to Infrastructure'* (2017-2020, £285k).
- Keylock - RAEng/Leverhulme Trust Senior Research Fellowship (2016-17, £53k).
- Oluwasola - RAEng Development Fellowship, '*Managing Agric-food chain waste using a synergy of conversion technologies*' (2019-2024, £604k).

The inclusive research and innovation ecosystem that we have created enables those at all career stages and from all backgrounds to flourish as contributors to our thematic areas, co-creating knowledge with our extensive academic and extra-academic collaborative network, and embedding positive, impactful change for the betterment of society.