Institution: Liverpool John Moores University

Unit of Assessment: UoA13

1. Unit context and structure, research and impact strategy

Unit context and structure

The Built Environment and Sustainable Technologies (BEST) Research Institute comprises of staff from the School of Civil Engineering and Built Environment in the Faculty of Engineering and Technology and was formally recognised by the University as a research institute in 2010. The aim of the research institute is to overcome civil engineering and built environment sustainability challenges by the use of novel technologies and management techniques in four core and one cross-cutting theme (34 FTE Category A staff) listed below. To achieve this the Institute's core strategy is to focus on strong external collaboration, establishing links with industry and the public sector in order to conduct research on priority areas addressing industrial and societal challenges and to fit within the UK and international strategies ("Grand Challenges"). The Unit's strategic focus on real-world challenges through collaboration is exemplified in the impact case studies submitted (ICS1, ICS2, ICS3). "Prolonging the Life of our Roads and Highways with No CO_2 Emission Construction Materials" (ICS1) resulted from a challenge for the pavement industry (Colas Ltd) to reduce CO_2 emissions, achieved by the development of new products helping them satisfy government CO_2 targets. ICS2, "Novel, non-destructive testing sensor platform for characterisation of insecticides and biohazards deposited on building materials" stemmed from collaboration between the Unit, the Liverpool School of Tropical Medicine (LSTM) and the Indoor Residual Spraying (IRS) teams from the Indian government. The technology developed by LJMU is impacting on government strategy and public health by reducing the burden of disease endemic to India. ICS3, "Low Carbon Solutions", emanated from the research and development of high efficiency energy from waste systems created for industry, dealing with different waste streams and the need to measure the carbon footprint of the technologies. This underpinning research led to the formation of the Low Carbon Innovation Hub, the Low Carbon Eco-Innovatory and the Clean Growth initiatives that have supported SMEs in the Liverpool City Region (LCR) to develop more sustainable solutions for their business and address the LCR grand challenges. The ICSs are outlined in more detail later in this section.

BEST leadership and governance

The BEST Steering Group (BSG) is responsible for the strategic oversight of research within the School of Civil Engineering and Built Environment, and is chaired by the head of the Institute (**Shaw**). The BSG meets on a bimonthly basis to oversee the direction and operation of BEST and comprises: School directors (**Al Khaddar** and **Cotgrave**), the 4 core theme leaders (**Shaw, Al Nageim, Maliene** and **Cotgrave**), the co-leaders of the cross-cutting theme (**Kot** and **Abdullah**) and the head of the research administration team (**Hoare**).

The BEST Research Institute has 4 core themes, with sensor development as a cross-cutting theme. (Leading staff members shown in **bold**):

- Radio Frequency & Microwave research – **Shaw**, Kot, Wylie, Hashim.
- Novel & bio-based materials –**Al Nageim**, Bras, Sadique, Yaboah, Gkantaou, Kamaris, Cebasek, Jemaa, Al-Mufti.
- Building engineering & construction practice – **Cotgrave**, Ahmad, Abdullah, Durson, Riley, Brady**,** Shah, Martin, Borthwick, Matipa, Siriwardena, Kurannen, Ojur.
- Sustainability & energy management – **Maliene**, Carnacina, Al Khaddar, Abdellatif, Loffill, Harris, Mulliner, Heinig.
- Sensor development – **Kot, Abdullah**, Shaw.

The Unit's **research strategy over the assessment period** has comprised 6 objectives:

- External funding will be sought from the EU Horizon 2020 programs, Innovate UK, Research Councils, Royal Society, Charities, directly from Industry and international grant awarding bodies (an increase by 30%).
- Continuation of expansion of the existing research groups in BEST, by appointment of new high calibre academic staff in accordance with the BEST and School's strategic plan.
- Enhancement of the research profile and activities of the ECRs and researchers at the medium stage of their career.
- Increase in the number of PhD recruited (increase by 35%).
- Continuation of existing and establishment of new research collaboration with leading international partners.
- An expansion of the collaboration with industry, both directly and indirectly through partnerships on externally funded research projects, with the view of maximising the impact of the research.

Evidence of the research progress made and delivery of the overarching strategy during this assessment period includes:

- £6.2M (REF4b) of income spent during 2014-2020 in comparison with £4.8m income spent in REF2014. The funds have been awarded from the EU, Innovate UK, Bill and Melinda Gates Foundation (BMGF), DSTL, Arthritis UK, research councils and direct from industry. [This is a 29% increase, 1% less than the target set in objective 1]
- Total of 34 FTE staff submitted in comparison with 17.2 in REF2014, with 17 ECR staff being recruited within this period. [This meets objective 2 with an increase of 100%]
- 3 Professorships and 2 Readerships have also been confirmed within this period. [This meets objective 3, with more detail in section 2]
- The number of students awarded PhDs has increased from 32 (REF2014) to 60 (87.5% increase). [This exceeds the target of objective 4]
- Sustained and/or established research leadership in national and international networks and forums. [The following demonstrates objectives 5 and 6 are being met, with more detail provided in sections 3 and 4]:
    - The submitted staff are influencing the international research agenda through both the sustained quality and volume of published output and membership of professional technical committees. **Bras** is a member of the International Union of Labs and Experts in Construction Materials, Systems and Structures (RILEM) technical committees (TC): TC 274-TCE: Testing and characterisation of earth-based building materials and elements and TC 275-HDB: Hygrothermal behaviour and durability of Bio-aggregate based building materials; SHE: Self-healing concrete-Its efficiency and evaluation. **Sadique** is an academic adviser on the Commonwealth Scholarship Commission (CSC), UK selection committee. **Marolt Cebasek** is a member of International Tunnelling and Underground Association and Committee for Education and Training (ITA-CET) representative for Slovenian Society for Underground Structures (SUSS). **Maliene** is the action vice chair of the "Public Value Capture of Increasing Property Values" (PuVaCa), European COST project action, which has representatives from 41 different countries. **Riley** served as chair of the Council of Heads of Built Environment. **Al Khaddar** served as President of The Chartered Institution of Water and Environmental Management (CIWEM) in 2015-16 and is now Honorary President. **Shaw** plays an active role in the All-Party Parliamentary Carbon Monoxide Group (APPCOG) and Carbon Monoxide Science and Technology Group (CO+SciTech), informing UK policy in relation to Carbon Monoxide safety. **Shaw** is also a trustee of the Gas Safety Trust and is on the research funding committee of the charity.
    - BEST has extremely strong industrial connections with employers (see section 3 'Income') and established relationships with professional bodies including: Royal

Institution of Chartered Surveyors (RICS), Chartered Institute of Building (CIOB), Chartered Institute of Architectural Technologists (CIAT), Chartered Institution of Water and Environmental Management (CIWEM), Chartered Institution of Building Services Engineering (CIBSE), Institution of Civil Engineers (ICE), and Institution of Engineering and Technology (IET). The Unit has staff with 7 fellowships from professional bodies - **Bras** was awarded Fellowship of the Institution of Civil Engineers (ICE) in 2019, the youngest woman to receive this award in the North West region.

- 64 invited keynotes/talks in 26 countries during the assessment period.
- External Visiting Professor posts have included **Carnacina** (UNALM, Lima, Peru), **Al Nageim** (Yantai University, China and University of Babylon, Iraq), **Riley** (University of Malaya, Malaysia and RICS SBE Delhi, India), **Al Khaddar** (Universities of Babylon-Iraq and Anadolu-Turkey), and **Maliene** (Vytautas Magnus University).
- 14 BEST research staff are also members of various Knowledge Transfer Networks (KTNs), Research Councils, editorial boards and advisory panels.

Knowledge exchange and impact generation strategy

Significant effort has been invested in transferring the Unit's research knowledge to industry. One of the Institute's objectives was an expansion of the collaboration with industry, both directly, and indirectly through partnerships on externally funded research projects, with the view of maximising research impact. This has been achieved through the strategic oversight provided by the BEST Steering Group, which encourages PIs to focus on the longitudinal aspects of the research from the outset, and horizon-scanning with their respective partner organisations for funding opportunities to progress a technological solution through the Technology Readiness Levels. The BEST Research Institute has generated the following types of impact:

- Economic impact: Innovative industrial processes and products; increased productivity, turnover and employment; and reduced industry waste and costs. (ICS1, ICS3)
- Environmental impact: Carbon footprint reduction by the efficient utilisation of novel materials and methods. (ICS1, ICS3)
- Quality of life impact: Contribution to public policy; public safety; improved health products. (ICS2, ICS3)

The research has had a direct quantifiable impact on regulatory and public policy, and the practices and activities of industrial organisations and services. The following exemplifies knowledge exchange and impact generation.

ICS1 – "Prolonging the Life of our Roads and Highways with No CO2 Emission Construction Materials": This impact case study derives from the research conducted by the Novel & bio-based materials research group/theme that facilitates sustainable and low-cost repairs, surfacing and maintenance of the existing asphalt, reducing the need for a complete resurfacing of roads. The application of thin layers postpones major repairs for several years and is suitable for all types of roads, therefore reducing the costs of major reconstruction works as well as reducing CO_2 emissions and preventing disruption to infrastructure users. Since developing new products based on the research at LJMU and developed with LJMU, Colas Ltd has increased annual sales by over €7m in the UK and France through laying over 850,000 m^2 of roads in 2018 and 2019 using the new product, with similar projections for 2020.

ICS2 – "Novel, non-destructive testing sensor platform for characterisation of insecticides and biohazards deposited on building materials": The underpinning research for this impact case study derived from the Radio Frequency & Microwave research theme. The focus on building substantive international links saw a small-scale 3-month study funded with a GCRF pump-priming grant evolve into a significant project with a major award from the Bill and

Malinda Gates Foundation (BMGF) in collaboration with the Liverpool School of Tropical Medicine (LSTM) and the Indian government IRS programme.
200 million people are at risk of visceral leishmaniasis (VL) globally; 65 million live in India, many in remote locations where medical assistance may not be readily available. VL is fatal if left untreated. Malaria is endemic in >30 countries and 200,000 children die from the disease annually. The VL and malaria parasites are transmitted through infected female insect bites, which require a blood meal to reproduce. An insecticide Indoor Residual Spraying (IRS) programme is the VL and malaria control measure recommended by the World Health Organisation. Quality assurance of the spraying is essential for effective disease control. The BEST research team has developed and operationally validated a self-contained sensor platform for IRS quality assurance. The prototype has been successfully field-tested in India, with orders in place for deployment and a patent filed in the UK and US. The sensor is also being prepared for the IRS market in malaria endemic countries globally. This research has led to extended product development, with funding from Defence and Security Accelerator (DASA) (£150k - 6 months) and BMGF (£1,01m total value, £456k to LJMU over 3 years) to explore sensing of biohazards and neglected diseases.

ICS3 – *"*Low Carbon Solutions": Low carbon solutions are the foundation of research activities undertaken by the Unit, focusing on carbon reduction technologies through energy from waste and waste management, low carbon planning, sustainable asset and energy efficiency management, and renewable energy. The ERDF-supported Low Carbon Innovation Hub (LCIH) and Low Carbon Eco-Innovatory (LCEI) projects both support and connect SMEs in the Liverpool City Region (LCR) with BEST researchers, introducing unique solutions to reduce their carbon footprint and linking these to applied research grant opportunities. The outcome of LCIH led to the generation of 42 additional jobs, safeguarded 30 jobs, and generated an additional £1.76m p.a. in Gross Value Added (GVA) for the LCR economy. The outcome of LCEI led to the development of 51 new to the firm products and saved 10,081 tonnes CO_2 in the period of 2015-2019. BEST researchers secured and completed an EU-Fast Track to Innovation grant that resulted in the plant scale installation of a microwave treatment solution for enhanced biogas production from pig slurry (Biowave^{TM}). The developed system increased the biogas yield from pig slurry by over 40% and a reduction of 37% of total CO_2 equivalent output of the farm per year.

Industrial collaboration and interdisciplinary research is at the core of BEST's research mission and is exemplified by the Unit's work with sensors during this assessment period. This cross-cutting theme stems from the REF2014 ICS "Impact of research into non-invasive sensors on industrial applications", and has evolved from a relatively narrow research base with wide applications to a wider academic base with focused, impactful applications such as the public health impact of detecting insecticide levels on walls in remote areas of India (**ICS2**) to reduce the incidence of vector-borne diseases. Extending beyond ICS2, the sensor research and development has included work with clinicians in collaboration with Alder Hey Children's Hospital and University of Liverpool in the development of a hip-dysplasia sensor to reduce the need for babies requiring surgery to correct this problem in later life (**Abdullah**). Also, work with Alder Hey Hospital and a local company (Care Innovation) in the detection of urea for an enuresis sensor is reducing both the number of young children needing to go to hospital and NHS waiting times, as well as child and parental anxiety (**Shaw**). Studies conducted with United Utilities (UU) have involved sensors to detect leaks and assets in water pipelines, and also substances of interest in water catchment areas. This research was funded directly from UU and supported 2 match-funded PhDs and £100k of specialised lab equipment to develop an underwater wireless sensor network to detect the presence and locate the source of pollution (**Shaw, Kot**).

BEST has also embraced interdisciplinary research by partnering with other Centres/Institutes in the Faculty with complementary expertise, e.g. the General Engineering Research Institute (GERI) (UoA12) and Data Science Research Centre (UoA11). The EU Horizon 2020 project DigiArt is illustrative of the Unit's approach to embracing and supporting this whenever an opportunity arises. BEST is the Lead Partner of a consortium that involves drone manufacturers and drone-based mapping specialists from industry; working together with archaeologists,

anthropologists, museum curators and art historians; and pan-EU researchers working in AR/VR technologies, Machine Learning, data mining and sensors. The BEST research group involves two PGRs with drones expertise affiliated to GERI. The project has supported their stipends and fees and provided an opportunity for interdisciplinary working.

Future strategic aims and goals for research and impact

In line with the University's research and knowledge exchange strategy and UK and international government initiatives and funding opportunities ("Grand Challenges"), the Unit plans to build upon the successes achieved during the REF2021 period. The Unit will continue to develop its infrastructure and knowledge base to provide researchers with an excellent environment in which to maximise research impact, sustainability and vitality. The prime vehicle for this is through the Low Carbon and Clean Growth ERDF-funded initiatives. Opportunities for further collaborative partnerships between BEST researchers and SMEs will develop through the dissemination events associated with these, where the BEST laboratory tours and presentations have proved to be highly-effective in generating new research associations. Continued support from the Faculty and University through pump priming activities (£200k invested in this period for BEST members) will allow these partnerships to develop and produce tangible benefits that will result in the application of external funding. The Unit through the BSG will support and encourage this activity to meet the following objectives.

The Unit's **strategic research and impact plan** has six key objectives:

- To extend the collaboration with government, industry and academic partners to identify and address key national and international research priorities, with the view of maximising the impact of the research.
- To develop paradigm shifting technological solutions for civil engineering and the built environment using RF and microwave methods.
- To expand novel, sustainable and bio-based materials for the pavement and building construction sectors, as low carbon solutions to prolong the life span of the structures.
- To improve the quality of life through providing dynamic novel solutions on air quality, thermal and lighting comfort, monitoring and control for building stakeholders.
- To generate and apply predictive models for community-based sustainable solutions with utilities management, flood defences and environmental impact, waste management and renewable energy management schemes.
- To enable the rapid transfer of research outcomes to business, the economy and society for impact generation, through the involvement of industry and societal stakeholders from the start of the research.

The Unit's **research and impact strategy** for the next REF cycle is to broaden its collaborative partnership for excellent impactful research; to extend the critical mass for enhanced research productivity and capability to tackle complex multi/inter-disciplinary research issues; and to foster research agility to embrace emerging research challenges and impact opportunities within its expertise areas. More specifically, the Unit will continue its research and impact approaches to develop fundamental solutions and integrate these into impactful applications. In particular, the Unit will invest more research efforts on the 4 core research themes and the sensor cross-cutting theme - one measure of success will be the expected increase of 33% in the number of impact case studies submitted. This will involve a further increase of FTE staff returned (increase by 45%) and a 50% increase in the number and quality of journal articles published. A final measure of success will be a 20% increase in the value of externally-funded research grants, with the income to be spent within the next REF cycle.

Open research environment and research integrity culture

The University supports open access (OA) publication to make research available to the widest possible audience. Since May 2015, the Faculty Research and Knowledge Exchange Committee (FRKEC) has consistently promoted the requirement that all Faculty research-active staff adhere to this process. The research outputs produced by the Unit over the assessment period have been OA-compliant and deposited through the University's institutional repository. There is a Faculty SharePoint for the deposition, sharing and reproducibility of the Unit's research data, with internal and external users having different levels of access. The University also has a data repository to ensure that the Unit is compliant with the UKRI Concordat on Open Research Data. Moreover, projects typically create their own websites (*e.g.* DigiArt) to disseminate research findings (*e.g*. through project reports for open access, and sharing unrestricted data to encourage further research).

A research integrity culture is fostered by the University Code of Practice for Research (last updated 2020/next review 2021) and promoted in new staff and PGR inductions. The Unit has a rigorous procedure in place for external grant applications, which have to be reviewed by two experienced researchers internally before submission. The University Research Ethics Committee (REC) implements governance arrangements to oversee the conduct of the Faculty's REC which in turn provides oversight, guidance and advice on the ethical implications of research proposals. Electronic records of all ethics applications are lodged in the Faculty's SharePoint. Zero allegations of research misconduct have been registered in the Unit during the assessment period.

2. People

Staffing strategy

The Unit adheres to the Faculty strategy of supporting all staff with the aptitude and aspirations of a career as an independent researcher – at all levels - to progress towards their research career goals.

Every ECR is assigned a senior researcher in the same Unit as a mentor, to review his/her performance, set objectives for the coming year and define a learning and development plan. Annual PDPR is monitored throughout the year and formally reviewed at the following year's meeting.

Staff recruitment and retention are at the heart of the Unit's research strategy. This is achieved specifically through the recruitment of internationally excellent researchers and provision of an excellent working environment that supports researchers' career development, recognises achievement, and rewards success. The Unit has supported 17 ECRs during the assessment period, and 2 Readerships (**Kot**, **Sadique**) and 3 Professorships (**Cotgrave**, **Shaw**, **Maliene**) have been conferred during this time.

The pattern of staff recruitment over the assessment period has seen the appointment of 16 staff with teaching and research responsibilities (4F,12M), two of whom completed their doctorates with the Unit (**Kot**, **Hashim**). Three established staff members completed doctorates during this period – including one from the Faculty of Health. All Category A eligible staff have permanent contracts, save for 3 researchers assigned to support the fixed-term European Regional Development Fund (ERDF)-funded Low Carbon Eco-Innovatory project, a joint project with the Universities of Liverpool and Lancaster, which links regional SMEs with the regional research base (ICS3). The Unit has a policy of assembling diverse research teams (evidenced in ICS1, 2 and 3), led by senior experienced researchers but including opportunities for ECRs and PGR students. This, coupled with the Unit's track record of rapid progression from modest pump-priming funding to major grant awards, attracts young international research talent on the cusp of an independent research career (**Abdullah**, **Bras**, **Kot**, **Mulliner**, **Sadique**).

Staff development within the Unit is a key aspect of creating a vital working environment that allows researchers to fully realise their potential.

Research staff joining the Unit participate in a formal induction process of preparation for their job role, providing them with the opportunity to learn about the University and their local working environment. This process is formalised by the FRKEC. All new staff are given priority in the allocation of internal funding through a number of schemes such as impact generation, pump priming, equipment support and studentships. There is a University policy governing sabbatical leave, that but no Unit staff have requested a discussion about this option.

The Unit provides a wide range of mechanisms to both support and develop staff engaged in research throughout their careers. The Unit engages in a comprehensive range of opportunities for all researchers (including PGRs) to develop their personal, professional and career management skills through the University's award-winning ACTivator programme. The regular courses offered include "Building Blocks of Impact", "Collaboration that Counts", and "Pitch Perfect" with staff from the Unit attending 49 sessions (2016-20), the most popular of which were "Funding applications -getting a yes" and "Ready, Steady, Publish". Online bookable services are also available for all researchers. For PGRs and PDRAs, there are further Researcher Development training courses offered on a quarterly basis, including "Researchers: Introduction to Your Support Network", and "Women Researcher Retreat". At Faculty level, experience-sharing workshops were organised 3 or 4 times a year where experienced staff share their good practice and lessons learnt with other staff in terms of successful grant applications to funding bodies. The Concordat has operated a robust action plan delivered through a Concordat Task Group and overseen by the URKEC. The performance of the staff development programme was recognised by the EU HR Excellence in Research Award in 2012 that was successfully retained following biennial reviews in 2014, 2016 and 2018.

An applied research ethos conducted in collaboration with industry partners is central to the BEST research mission and provides a staff development opportunity. During the assessment period, the Unit has directly supported five of the Faculty's eight ERDF projects – LCR4.0 (2016-19; 2019-22), Low Carbon Eco-Innovatory (3 consecutive programmes 2015-19; 2019-20; 2020-23), Future Energy (2017-18), Low Carbon Lancashire Innovation (2017-20) and the sensors element of Liverpool City Region Green Sustainable Travel Corridors (2019-21) – and the Sensor City University Enterprise Zone 2014-17 (BEIS); 2015-21 (ERDF). These have provided a mutually useful training ground for those ECRs without industry links. An example is the postdoc who having completed his sensor-related PhD with the Unit, had the opportunity of delivering the ERDF LCR 4.0 project to the regional SME business base, as an industrial software specialist based at Sensor City. During this period, he worked with 30 companies to adopt Industry 4.0 technologies and gained useful experience of identifying and providing solutions to industrial challenges. At the project close in September 2019, he joined the Unit as a lecturer and active research member (**Muradov**).

Research students

The Unit's PGR students are co-located in open-plan offices alongside established researchers and support staff, to fully-integrate them within their respective research labs/hubs (industry-related; sensors/UAVs; or materials and the built environment). They are encouraged to attend the regular Faculty experience-sharing workshops, delivered by Faculty researchers who have received awards from the major funding programmes (BEST researchers have contributed to the EU, ESIFS and Innovate UK sessions). **Kot** attended an EU funding workshop (28/02/18): *"This event was significant in helping me to develop my research career. At that time I was a Research Assistant who had just completed PhD studies and didn't have any previous experience with funded research. This event encouraged me to explore various routes for research funding and apply skills gained during the event to prepare research proposals. Since than I have applied for over 20 externally funded grants and secured over £1.5million (LJMU*

Income) as the Principal Investigator (PI) and £2million (LJMU Income) as Co-investigator (Co-I) with the help and support from the Faculty Dean, Head of BEST Research Institute and my colleagues within the research group and in other departments and faculties. This has also resulted in my career progression to a current role as a Reader in sensor technologies."

Once a year, all BEST PGRs are required to deliver a short seminar on their own research at the monthly meetings of Research Institute staff and students. *"My experience doing a PhD at LJMU pushed me in a number of ways. Above all, it strengthened my research and presentation abilities, particularly the opportunities to pitch my research to Institute research teams as part of the mandatory seminar series, and to my peers and industry guests at the annual Research Week. Such activities helped me considerably in developing my communication, organisational and administrative skills that have proved to be essential requirements for my current role as a Research Assistant with the Low Carbon Eco-Innovatory project"* (Shubbar/**(DoS) Sadique**).

In addition to the University and (mandatory) Faculty induction events, the Unit's PGR students are encouraged to take full advantage of the University's suite of PGR training and career development opportunities (Doctoral Academy; ACTivator programme; Research Cafes; 3-minute thesis (3MT) competition; annual Research Day). During writing up, PGR student (Frau/**(DoS) Wylie**) has been supported by the Doctoral Academy Thesis Boot Camp (30/08/19-3/09/19) and subsequently registered for 18 writing workshops between March-September 2020. *"I can say the Boot Camp reset my way of writing and daily writing routine. On Monday morning, we (a group of 15 ECRs from across the University) arrived at the Gladstone's Library in Wales, a beautiful and inspiring place, just the right ambience for producing some work. Then we spent two days of immersive writing, with the necessary breaks and social activities. We learned to set and achieve our goals, using alternative approaches to writing, eliminating temptations. We also learned the need and advantage of rewarding ourselves. After this successful experience, I have attended every writing session organised by the Doctoral Academy: every first Friday of the month and every Wednesday afternoon, which moved online during the COVID-19 national lockdown. This helped me a lot with my PhD thesis writing, especially considering the working from home, by ourselves, without the office or library environment and colleagues. I managed to submit my PhD thesis at the beginning of July 2020 and successfully defended my thesis at viva in September. The writing workshops have helped me in four ways – developing a writing routine; setting realistic goals, tracking progress and achieving; creating my own writing zone but also understanding the benefit of having a writing community. I apply my learning from these workshops on a daily basis. I am now more effective with Journal articles, job and research grant applications."*

The Faculty offers two unique support programmes: 1) The PGR Reps' Society meets monthly and holds regular social and career events. Its current Vice-President is a BEST PGR, and the Society feeds back on PGR concerns to the University Research Degrees Committee, which meets 5 times a year. 2) The PhD student mentoring scheme is a voluntary support programme of experience-sharing and signposting, administered by the Research and Enterprise administration team and supported by two academics from BEST. Although unpaid, the Faculty pays for mentors to undergo the ILM Coaching and Mentoring programme, which adds value to their CV. "*The Faculty's mentorship scheme was an essential part of my PhD journey at LJMU — both as a mentee and mentor. The most significant benefit of my engagement with the program was that it opened up a seemingly solitary world of my own PhD research, by highlighting that even though PhD candidates may be working in vastly different research areas, we were all following a similar path. This encouraged me to engage and discuss my own PhD work with my mentors, mentees and other researchers (many of whom I now call friends) and develop a research network throughout the Faculty. This network has allowed me to point researchers struggling with their own research activities to relevant academics and other researchers who either know their respective fields or may have potentially valuable insight into them. The mentorship scheme and its associated Mentoring and Coaching training played a part in helping me to secure my current role as a Research Assistant at the university - a job in which I now engage with other researchers from across the University to assist the region's SMEs with*

low carbon innovation opportunities through the Low Carbon Eco-Innovatory project" (Kelly/(DOS) Blanco Davis).

Similarly, PGRs that express interest in teaching and/or demonstrating must undergo the Advance HE (formally HEA)-accredited '3is' programme (a compulsory requirement), which can lead to Associate Fellowship status. *"Taking part in communication-led activities such as 3is and 3MT have allowed me to work on my delivery and public speaking skills and ensure my scientific communication is both dynamic, effective and adaptive to the audience. Whilst the 'building blocks' of these skills are built during undergraduate degrees and developed during PhD study, without taking part in these extra activities I do not feel I would be as skilled or developed, which enabled me to stand out in the recruitment campaign for my postdoc role."* (Romano/**(DoS) Bras**, PDRA in Marine Technology at LJMU on the Interreg Atlantic Area-funded EMPORIA4KT project (EAPA_842/2018, 2019-22).

All Faculty PGRs pitch their research to peers, academics and invited industry guests at the annual Faculty Research Week in May. Since its inauguration in May 2015, the Unit's PGRs have secured 29% of the total prizes awarded (there are seven research units in the Faculty), claiming a third of the possible awards for 'Best technical paper' (Wijekoon/**(DoS) Ross** 2016; Frau/**(DoS) Wylie**, and Al-Attabi/**(DoS) Harris** 2017; Randles/**(DoS) Cotgrave** 2018; Amin/**(DoS) Abdullah** 2019) and 'Best potential impact' (Hashim/**(DoS) Shaw** and Dulaimi/**(DoS) Al Nageim** 2016; Sindhu/**(DoS) Maliene**, and Cashman/**(DoS) Wylie** 2017; Romano/**(DoS) Bras** 2018).

During this assessment period, 6 PGRs have been awarded prizes at international conferences (ICST-2015, Auckland; BUiD-2016 (Unterhitzenberger) and -2017 (Dulaimi), Dubai; DESE-2018 (Ryecroft), Cambridge; WWEM-2018 (Frau), Telford; ICST-2018 (Frau), Limerick). A PGR from BEST (Dulaimi) was awarded the Iraqi Cultural Attaché Prize 2017 for best PhD achievement (17 publications) at an awards ceremony attended by the Iraqi Minister of Higher Education and Scientific Research) and the Ambassador. In 2017, 20% of the 21 top Iraqi PhD students in the UK selected to attend the event were affiliated to the Unit.

Equality and diversity

The University is committed to cultivating an inclusive and accessible academic environment. In line with the institutional Inclusive Practice Strategy (2016-2020), the Unit encourages staff and research student declaration of protected characteristics. The Unit adheres to the LJMU Code of Practice for REF2021, which defines the process for SRIR, staff declaration of circumstances that have prevented research productivity and how R-only staff can be considered as independent researchers. The Faculty's designated EDI Champion (Johnson) ensures Unit-level equality and diversity policies and practices are aligned with those of the University as a whole.

Each member of the staff is required to complete an online training course on the issues of equality and diversity annually. Among the 34 Category A staff returned to this UoA, 41% are from BAME backgrounds; 11 (32%) are women and 6 of whom have been appointed as lecturers since 2014. The outputs have been submitted with an average of 2.5 per female staff and 2.4 per male staff. Examining the outputs with reference to ECRs shows on average 2.6 outputs per ECR and 2.3 per staff for non-ECRs. All academic and research staff are eligible to access a range of family-friendly options (*e.g.* maternity, paternity and adoption leave; parental, compassionate, domestic and personal leave). They are also entitled to take sabbatical research leave (**Al Nageim** 2014-2015) that is locally supported. All training and support programmes are consistent with the Concordat to Support the Career Development of Researchers and respect equality and diversity. The Unit can cite three practical manifestations of this commitment during the assessment period. 1) The Unit has provided designated accommodation for quiet reflection/prayer and the research schedule accommodates Friday prayers for Muslim research staff; 2) the Unit is currently supporting a PGR through gender reassignment. The PGR feels at ease amongst peers and the research community in the University environs, progresses their research studies, but is exempted from presenting to the industry partners. Their supervision

team deliver this element. 3) Faculty Research Week has fallen during Ramadan three times since 2015. As such, the delivery of the refreshment and lunch breaks was conducted with consideration for those present who were fasting.

All buildings associated with BEST's research are Disability Discrimination Act (DDA) compliant and all research staff and students are supported by the University's dedicated and comprehensive resources to support any form of registered impairment.

3. Income, infrastructure and facilities

Income

BEST research income spent in the period 2014 to 2020 was £6.2m (REF4b) which is a 29% increase from REF2014 (£4.8m). This reflects the increase in the critical mass (34 FTE in this period from 17.2 REF2014), the novelty and uniqueness of the research and the shift in culture due to the support put in place for staff to engage more with these activities. The following are examples of some of the awarded grants.

Research income: External collaboration and interdisciplinary research have been at the core of the BEST research mission from the outset. This can be exemplified by BEST's work with sensors during this assessment period with focused, impactful applications in a societal and public health context. One source of funding suited to that aspiration are the research support opportunities offered by charities, and in this period the Unit has been granted £1.5m of funding from sources such as Arthritis UK, Gas Safety Trust and the Bill and Melinda Gates Foundation (BMGF). The latest funds from BMGF with LSTM as collaborators was for £586k to LJMU for the research and development of a microwave sensor to detect 6 different insecticides on differing building materials in Africa.

With a more industrial collaboration focus, the Unit secured £600k of funding from Innovate UK and a further £430k direct industrial support from United Utilities, Boston Garages, Balfour Beatty and Road Mender Ltd, Stopford Ltd, and the Home Office.

BEST was the Lead Partner of the H2020-funded DigiArt consortium, which has included researchers from the UK, Belgium, France, Greece, Switzerland and has harnessed the knowledge of disciplines including computer science, archaeology, palaeontology, art history and engineering (DigiArt, 2015-2018, €3m project, €2.4m EU funding, €800k to the Unit).

Impact generation income: Within this period (2014-2020) the Unit's research income for impact generation was £3.1M and included 4 KTPs totalling a grant income of £557,915 with Beverley Clifton Morris Ltd, Beverston Engineering Ltd, United Automation Ltd and Colas Ltd, the latter leading to an impact case study (ICS1).

The Unit has supported 2 Fast Track to Innovation EU Horizon 2020 projects. **BioDie2020,** 2016-2019, €2.8m project, €2.1m EU funding, €579k to the Unit as a partner, was led by Argent Energy (UK, INDUS) and included BDI (Austria, SME), Stagecoach (UK, INDUS) and Quantis (France, SME). **Biowave™**, 2016-2018, €1.9m project, €1.36m EU funding, €175k to the Unit as a subcontracted consultant, involved Ashleigh Farms Limited (Ireland, SME) as the lead partner, Methan O'Gen (UK, SME), Gilmore & Clarke (Electrical) Limited (Ireland, SME) and Sairem (France, SME). The latter led to ICS3.

BEST research has directly underpinned 2 regional projects supported by ERDF funds; **Low Carbon Innovation Hub**, 2013-2015 of £1.1m of which the EU funded £550k, and the **Low Carbon Eco-Innovatory**, 2015-2019 of £2.58m of which the EU funded £1.29m.

Infrastructure and Facilities

Full-scale experimental research houses: During the assessment period, there has been significant investment in the infrastructure supporting BEST research and impact. In partnership with the Building Research Establishment (BRE), four full-scale houses have been built on the Unit's campus between 2015 and 2019, to the building codes of the 1920s, 1970s, present-day and a modular build, as part of the BRE Innovation Parks Network. This represents a £468k investment in research and test facilities. These facilities have been used for testing the risk for CO migration from a source in one terraced house to the adjoining properties. This was conducted with the Merseyside Fire and Rescue Service (FRS) to also ascertain whether the advice to switch off the source, open a window and leave the property was correct. The facilities have also been used by several SMEs examining new building products from solar blinds to new heating systems, to validate their products in a real-world controlled environment as part of the Low Carbon Innovation Hub and the Low Carbon Eco-Innovatory projects. The modular home has led to the delivery of a series of collaborative programmes of research into the new prefabricated home's performance. This has included testing to understand the full environmental qualities of the properties, along with the creation of a new model and framework to assist in creating truly cost- effective zero carbon housing developments. This work was undertaken with Urban Splash as part of the Low Carbon Eco-Innovatory (LCEI) project (£70k). The research houses have also led to cross UoA collaboration such as a joint PhD entitled "Risk detection for the prevention of falls on stairs in older people", which involved the sensor knowledge from BEST being coupled with the biomechanics team in the Research Institute for Sport and Exercise Sciences (UoA24) to determine what causes the highest risk for elderly people falling on staircases. The outcome of this are recommendations for stairs adaptations for assisted living and smart homes.

Sensor City University Enterprise Zone: BEST was involved in the co-design of the four Sensor City UEZ labs for industry-research collaboration (£15m BEIS-Liverpool City Region investment, opened 2017), and have access to these as one of the founding members. These facilities have allowed the fabrication and demonstration of several sensor prototypes that resulted in the start of the collaboration with LSTM and led to the BMGF projects (ICS2). The facilities have hosted several industrial networking events including SAMSA as well as ministerial visits (Business Secretary Greg Clark, Nov 2017; Margot James (DCMS) and Philip Hammond (Treasury), Feb 2019) again showcasing the sensor work from BEST. The Unit also showcased the results from DigiArt as part of the LightNight Liverpool event where over 100 general public visitors experienced a demonstration created by BEST staff of the 3D reconstruction and gamification of cultural heritage sites such as the Scladyna cave and the virtual anthropology museum.

High Performance Computing (HPC): In 2016, the faculty invested £250k to have two relatively small, 112-core and 244-core HPC computer clusters. Various commercial and in-house software including CHAPSim CFD, OpenFOAM, Flexsim, DNV-GL Sesam, Ansys-Fluent and Abaqus are currently run on the cluster by the researchers undertaking simulations in the areas of CFD, offshore renewables, materials, laser technologies, naval architecture, fire and smoke modelling, system dynamics, and astrophysics. In 2018, the Unit invested £250k to enhance the HPC facility with1000 Intel Xeon Gold (Gen10) cores @ 2.5 GHz, a RAM of 13 TB, high speed (100G) infiniband interconnect (for parallel jobs with high communication loads) and 1 PB of storage of connected storage. In 2019/2020, the Unit has further invested £450k to enhance the HPC through adding a "Tier-3" facility to facilitate diverse research computing applications and to act as a development bridge from desktop computing to the national (Tier-1) and international (Tier-0) HPC research facilities available to UK academics via Archer, DiRAC and PRACE. The facility can be used both as a "work farm", capable of running many independent computing tasks simultaneously (*e.g.* image processing), and as a massively-parallel computer capable of running individual jobs (*e.g.* fluid dynamics calculations). It comprises 1,280 AMD Rome processing cores in 20 high-density HPE Apollo compute nodes, networked with the high-bandwidth, low-latency HDR Infiniband fabric. The facility has a total

memory footprint of 10TB and a long-term storage capacity of 1.5PB provided by a parallel BeeGFS filesystem. This facility is utilised by all of the groups for intensive modelling of different systems such as electromagnetic mode propagation in waveguide structures or plasma torch characteristics and also complex water flow characteristics.

The **Sensors and UAV Laboratory is a newly formed lab with** £100k internal investment to expand and upgrade the infrastructure to accommodate the growth in sensor-related research projects and is a shared resource with the GERI (UoA12). This laboratory supported the completion of the EU-funded DigiArt project and both the Beverston Engineering Ltd (£147k) and United Automation Ltd (£171k) KTPs, along with several healthcare-related projects. The laboratory has state of the art facilities including a microwave 4-port network analyser (£120k), Digital Microscope (£50k), electronics prototyping test and evaluation equipment (£60k) and a certified EMC chamber for sensor development (£100k), and is primarily used by the Building Engineering researchers.

The **Industrial Laboratory** is dedicated to income generation projects, which also fund the required improvements to the laboratory. This laboratory is used by the RF & Microwave researchers and houses £1.2M of specialist equipment primarily for energy from waste and industrial sensing and process enhancement. Within this period the laboratories have been used to create a pilot plant for the EU-funded BioDie2020 project (€2.1m), a test facility for the waste substrates in the EU-funded Biowave™ project (€1.36m), and the sensor platform development for United Utilities (£160k). The equipment in the laboratory includes Microwave sources (£150k), Gas detectors (£20k), Automation and control (£40k), High Performance Liquid Chromatography (HPLC) unit (£30k), CEM microwave unit (£35k), Fermenter/ bug lab (£50k), Sensor Printed Circuit Board (PCB) multilayer machines (£25k), Microwave signal generators and Vector network analysers (£400k).

The Concrete and Materials Testing Laboratory for pavement and road engineering, asphalt and aggregates facilitates mixing equipment and cement making (£70k). This laboratory is used by the Novel & Bio-Based materials researchers to develop sustainable concrete mixes and cold asphalt binders for industry including Colas Ltd, United Utilities and Tarmac, and is where ICS1 was completed. The **Bio-Based Materials Testing Laboratory** is the base for the development and testing of differing bacteria in concrete mixes for the research and development of self-healing concrete. The facilities include an environmental test chamber (£60k) for testing and evaluating building materials including freeze thaw cycles at controlled temperatures between -20 to 50 degrees C. The facility also has a clean room with appropriate fume extraction and PPE for the culture and growth of different bacteria. This laboratory is used by the Novel & Bio-Based materials researchers to develop their novel bio-based products in a controlled environment.

A **Geotechnics Laboratory** is available for the testing and identification of the properties and strength parameters of material such as soils, and to test elastic and plastic deformation of structures. This laboratory is use by the Novel & Bio-Based materials researchers to characterise and test the new structures.

The Hydraulics Laboratory for water and wastewater treatments provides industrial prototype systems and flow channels or testing and evaluation. This laboratory is primarily used by the Sustainability & energy management research team to model coastal erosion, flood defences and bund wall failure experiments. Recently the novel sensor work being developed in the RF & Microwave research team are using these facilities to test the sensors in identifying different pollutants propagating in the water flow.

Future opportunities for the Unit's facilities and impact generation lies with a recent £18.6m grant from UKRI Strength in Places Funding, which is an LSTM-led consortium with the Unit leading a work stream in the research and development of non-invasive diagnostic platforms and receiving £387k of funding to equip a new laboratory in the new Liverpool Life Science Accelerator building. The new laboratory facility will allow the continued expansion and strengthening of BEST's cross-cutting sensors theme, with particular focus on public health-related applications.

Supporting impact-generating activities

While the members included in this submission have actively expanded their existing impact generation, much effort has been made in developing new industrial impact in both traditional and emerging research areas. One way in which this has been achieved is through the Low Carbon Innovation Hub and Low Carbon Eco-Innovatory grants. Academic staff are introduced to industry, discussing their challenges and potential solutions and encouraged to participate in KTPs or Innovate UK calls to take this further. The 2 KTPs with Beverston Engineering Ltd and United Automation Ltd both developed through this route. Another support mechanism has involved utilising the industrial tours of the laboratories listed above that occur on a regular basis through the ERDF programmes. Examples of the outcome of this are the EU-FTI BioDie2020 project (€2.1m) with Argent Energy and the collaboration with the Liverpool School of Tropical Medicine, which led to (ICS2) and a £1.5m project with the Bill Gates and Melinda Foundation (BGMF).

The Faculty has a scheme dedicated to giving a commensurate reduction in teaching/administration duties to each academic member for industrial impact-generating activities. The Faculty has also provided funds to support academic members for industry visits for possible impact generation and to attend national and international sector conferences. Furthermore, the Unit has organised impact-generating workshops with invited industry specialists.

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

Collaboration & Partnerships

Collaborative research is strongly promoted and supported at all levels in the Unit and Faculty and is underpinned by the University's Research & Innovation Services, which coordinates initiatives to stimulate internal collaborative working and facilitates external engagement by providing a supportive service in all matters pertaining to intellectual property, patents, commercialisation and legality of contracts. The Unit has also benefited from the match-funding of collaborative activities with industrial partners from the University and Faculty. Examples include 4 PhD projects (United Utilities (2), Matrix Polymers and Walton Hospital partners) match-funded by the Faculty over the assessment period.

The University also supports international collaboration by offering Global Challenge Research internal Funding grants. Examples follow of the use and impact of these grants by Unit staff. **Sadique** collaborated with a public university (CUET) in Bangladesh with the resulting research showing the potential of developing clay-free unfired bricks using locally-available industrial waste streams. The findings of the study was awarded best paper in an international conference in Bangladesh (ICCESD 2020) sponsored by ICE, UK. The creation of a network with Pokhara University in Nepal (**Shah**) resulted in several research funding opportunities. **Marolt Cebasek** networked with North Macedonia creating the initial collaboration for further grant opportunities. **Karamaris** used it to expand their network and strengthen their collaboration with the Central South University in China. The outcome of the GCRF-supported "Feasibility study to explore the use of electromagnetic spectroscopy techniques to detect lymphatic filariasis microfilariae in blood" (**Kot**) led to securing external research funding conducted in collaboration with the LSTM and India, funded by the Bill and Melinda Gates Foundation (total grant value $1,300,000; LJMU- $600,000).

The Unit makes strategic use of available pump-priming funds (offered by the Faculty), to generate early-stage impact that can inform and strengthen applications to external funding bodies in a competitive bidding environment. ICS2 is an example of this. At the other end of the spectrum, ECR (**Bras**) has built on an Innovation Voucher award (£10k, 1Q 2018) and

subsequent LJMU/GCRF Small Grants funding (£13k, 1H 2019) to secure two grants from the Royal Society (£20k, 2019-2020) and ICE R&D Enabling Fund (£25k, 2019-2020).

Building on previous research for the Gas Safety Trust highlighting that carbon monoxide levels in social housing had been historically under-reported, (**Shaw**) led a collaborative research project with FRSs in Merseyside, the West Midlands, Cornwall, Bedfordshire and Oxfordshire and the Council for Gas Detection and Environmental Monitoring (Gas Safety Trust, 2014-2018, £89k). The study was set up to provide a more detailed picture of the potential long-term health effects of chronic low-level exposure to carbon monoxide in domestic dwellings, and the results were presented to the All-Party Parliamentary Carbon Monoxide Group (APPCOG), Chief Fire Officers Association (CFOA), IGEM and ICON conference as a keynote speaker. As 'trusted messengers', FRS personnel collected the data from households. The research team at LJMU included academic researchers from Public Health, Nursing, Psychology, Computing and Mathematical Science, co-ordinated by BEST. Supervised by Shaw, a Faculty of Health staff member completed her PhD ('Coping with Carbon Monoxide (CO) exposure; An interpretative phenomenological analysis') in 2018. Shaw was invited to join the Carbon Monoxide Science and Technology' Group (CO+SciTech) affiliated to the APPCOG. The group draws together a range of professionals and organisations concerned with either research or the development of technology in the field of carbon monoxide and other harmful by-products of burning fossil and other fuels. Chaired by Cranfield University, the group enables researchers to share knowledge with one another, and showcase their work to industry, parliamentarians and the media. In 2017, Shaw was invited to be a trustee of the Gas Safety Trust to support their research grants committee in the continued funding of Carbon Monoxide research.

DigiArt's principal aim was to make the large-scale 3D capture of cultural assets and their subsequent presentation in an augmented or virtual reality setting a practical reality. The project has made a significant advance in the efficient 3D capture of cultural heritage artefacts of widely varying scale, ranging from desktop to macro-graphic sites. The project provided a rare opportunity to access accessible and less accessible sites for 3D visualisation, and contributed to the effective manipulation of such 3D data, including in particular the registration and combination of 3D data originating at different times, and from different modalities. The conducted work has contributed to improved efficiencies in the curation of digital collections, via the development of semi-automated tools for the semantic classification of 3D digitised objects. Finally, DigiArt contributed to the development and demonstration of tools for the creation of narratives that will unfold in AR or VR, allowing the interlinking of captured artefacts, perhaps physically separated, in informative, educational and illustrative scenarios. The 7 project partners were from a multi-disciplinary background such as anthropologists, museum curators, computer scientists and engineers from UK, Belgium. France and Greece. Since this concerned cultural heritage the dissemination events included the public, politicians and scientists.

Contribution to the research base

Indicators of wider influence, contributions to and recognition by the research base have included:

- 27 journal editorships. Examples: Sustainability (**Gkantou, Mulliner, Maliene**); Built Environment Project and Asset Management (**Siriwardena**); Journal of Construction Research (**Shah**); Water and Environment Journal (**Al Khaddar**); Construction Innovation (**Al Khaddar**); Electronic Letters (**Shaw**).
- 64 invited keynotes/talks in the following countries: UK, China, Ireland, Brussels, USA, Malaysia, Brazil, Hong Kong, Japan, Morocco, Pakistan, Nepal, Germany, Poland, Turkey, Cyprus, Greece, Spain, Peru, Netherlands, France, Ukraine, Russia, Lithuania, India, Iraq and Sri Lanka.
- 7 Fellowships of professional bodies; Institution of Civil Engineers (**Bras**); British Institute of Non-Destructive Testing, Chartered Institution of Highways and Transportation (**Al Nageim**); Royal Institution of Surveyors Malaysia, Association of Building Engineers, Royal Institution of Chartered Surveyors (**Riley**); Chartered Institution of Water and Environmental Management (**Al Khaddar**).

- 15 Visiting Professorships in China, Iraq, India, Malaysia, Lithuania and Peru, e.g. Yantai University, China (**Al Nageim**); University of Babylon, Iraq (**Al Khaddar**), RICS, SBE Delhi, India (**Riley**); UNALM, Lima, Peru (**Carnacina**).
- 2 Visiting Researchers; Environmental Research and Studies Center, University of Babylon, Iraq. (**Hashim**); Warsaw University of Technology, Faculty of Geodesy and Cartography, Poland (**Kot**).
- (**Al Khaddar**) 29th President of the Chartered Institution of Water and Environmental Management (2015-16).
- Academic adviser on the Commonwealth Scholarship Commission (CSC), UK selection committee (**Sadique**).
- Member of the CIOB Accreditation Panel that develops the Educational Framework for professional accreditation at undergraduate and postgraduate levels and assesses programmes and Institutes in gaining Accreditation status for Programmes and Universities globally (**Borthwick**).
- Member of the Merseyside and North Wales CIBSE group coordinating professional practice activities in the region. Member of CIBSE Industrial Liaison group and symposium scientific committee (**Brady**).
- International Tunnelling and Underground Association – Committee for Education and Training (ITA-CET) representative for the Slovenian Society for Underground Structures (SUSS), (**Marolt Cebasek**).
- Secretary of the Slovenian Society for Underground Structures (**Marolt Cebasek**).
- Scientific Committee member of the CESARE 2022 conference in Jordan, STEPS 2020 in Iraq (**Gkantou**).
- Advisor to National Express Group PLC on Property Management, Dilapidations and Carbon Management for the Transport Sector (**Riley**)
- Member of RICS UK Education Standards Board (**Riley**).
- Academic Assessor of RICS Assessment of Professional Competence (UK, Malaysia and Hong Kong) (**Riley**).
- Chair of Council of Heads of Built Environment (**Riley**).
- Member of the Environment Advisory Panel, Canal and River Trust (**Al Khaddar**).
- Member of EWRI International Participation Committee (IPC) (**Al Khaddar**).
- Committee Member of Liverpool City Council School Safety and Air Quality Scrutiny Panel (**Abdullah**).
- Committee Member of the Chartered Institution of Building Services Engineers (CIBSE), Merseyside and North Wales (**Abdullah**).
- Qatar National Research Foundation (**Al Nageim**).
- Chair and founder of the annual international conference on sustainable construction materials, pavement engineering and infrastructure; since 2001 organised in association with Colas Ltd, Nynas Bitumen, ASI Solutions and RSTA Ltd. (**Al Nageim**).
- Member of the Education and Professional Development Committee, British Institution of Non - Destructive Testing, UK. (**Al Nageim**).
- Executive Board member of the European Academy of Land Use and Development (EALD) (**Maliene**).
- Member of the Board of the European Working Group of the Association of European Operational Research societies (**Maliene**).
- Networking Project - Public Value Capture of Increasing Property Values (PuVaCa), European COST project action CA17125, 2018-2022, Value -480,000 Euros (co-proposer; vice chair of action, MC for the UK, Co-I) (**Maliene**).
- Building Information Modelling based tools & technologies toward fast and efficient RENovation of residential buildings (BIM4REN), H2020 Grant ID: 820773; 2018- 2022, Value -6,997,515 Euros, contribution in kind -60,000 Euros (adviser). (**Maliene**)
- Member of the International Union of Labs and Experts in Construction Materials, Systems and Structures (RILEM) technical committees (TC): TC 274-TCE: Testing and characterisation of earth-based building materials and elements and TC 275-HDB: Hygrothermal behaviour and durability of Bio-aggregate based building materials; SHE: Self-healing concrete–Its efficiency and evaluation (**Bras**).

- Member of CA COST 15202 SARCOS-Self-healing As prevention Repair of Concrete Structures (**Bras**).
- Participation in strategic international committees including RILEM, Indian Concrete Institute (ICI), fib (Fédération internationale du béton), COST 15202 and ICE NW Fellows Network, enables contribution to drafting guidance documents that will inform practitioners and increase impact on the performance of structures and buildings (**Bras**).

Contribution to the economy

The Unit has contributed to the economy in five areas: Through **innovative industrial processes and products** (the novel surfacing materials developed with Colas Ltd (ICS1) have resulted in increased annual sales of €7m; 51 new-to-firm products developed through the LCEI (ICS3); IRS QA sensor solution, with UK and US patents pending (ICS2); four KTP projects; SMEs including Urban Splash have used the experimental research houses to validate new low carbon products in a real-world controlled environment. **Increased productivity** has been achieved through the LCIH (ICS3), which has generated an additional £1.76m a year in GVA for the Liverpool City Region economy, and also realised **increased turnover and employment** through the creation of 42 new jobs with 30 jobs safeguarded. The work with Biowave™ (ICS3) has resulted in a new product and **reduced industry waste and cost** through enhancing the biogas yield from pig slurry by >40%. The LCEI project has resulted in **carbon footprint reduction in the business base**, with 10,081 tonnes of CO_2 saved between 2015 - 2019.

Contribution to society

The Unit has shared its research with a diverse range of different publics during the period of assessment, from international audiences to local primary schools based in areas of deprivation. For instance, (**Shaw**, **Kot**) demonstrated the novel digital technologies developed as part of the DigiArt project at a 'Digital Single Market – Achievement and Challenges' event at the European Parliament, Brussels, to an audience of 70-100 journalists from the 28 Member States. At the other end of the engagement scale, for the last two years the Unit has hosted half-day visits from a Bootle primary school to explore sensor and drone technologies. "The children got a lot out of the sessions and it has opened their eyes to what a university does and the opportunities that are out there on their own doorstep" (Deputy Head).

As a further example of contribution to society, the entire LJMU Year 2 Primary Education student-teacher cohort spent 2 days at the school in January 2019, planning and teaching Science, Design and Technology to 120 children. It was hugely successful, for both pupil enjoyment and learning, and gave the LJMU student teachers an opportunity to teach creatively in teams – rarely experienced on a teaching placement (Primary Programme Lead feedback). Other examples of public engagement have included an Art of Technology installation at Sensor City as part of the city's annual one-night arts festival (LightNight Liverpool) in 2017 and 2018.