Institution: **Loughborough University**

Unit of Assessment: **C16 Architecture, Built Environment and Planning**

a. Overview

The 33 staff in the Built Environment Unit are part of the School of Civil and Building Engineering at Loughborough University (LU), one of the UK's largest self-contained interdisciplinary schools of the built environment; the remaining 33 staff are returned under UoA B14. The Unit is an internationally recognised centre of excellence in ***Building Energy Demand*** and ***Construction Technology and Organisation,*** a reputation founded on high quality application-focused research conducted within a world-class research environment. Staff are drawn from diverse backgrounds, enabling us to tackle many social, technical and economic challenges confronting the built environment through inter-disciplinary research programmes. A particular feature is the extensive collaboration with academics from other LU schools and other world-leading research teams.

We have grown in line with our RAE2008 aspirations, in terms of staff returned (+16%), research spend (+117% p.a.) and the quality, significance and impact of our outputs (Table 1 and Section e). Our achievements were underpinned by a £2.1m capital investment in research facilities and infrastructure (Section d) and the successes of our two EPSRC-funded centres for doctoral training (Section c). In line with our RAE2008 and future research strategies (section b), we have refined our interlinked research themes to reflect our increasing emphasis on sustainable practices in the built environment. Our burgeoning *Building Energy Demand* research focuses on sustainable design and operation of new/existing buildings, whilst our established *Construction Technology and Organisation* research addresses the production and operation of high-performance built assets and systems. Our established research centres, the Engineering Construction Institute (ECI), the Centre for Innovative and Collaborative Construction Engineering (CICE) and the London-Loughborough Centre for Doctoral Research in Energy Demand (LoLo), are bridges to our stakeholder constituencies and provide critical mass around particular research challenges.

b. Research strategy

We set our strategic areas for growth and development in RAE2008 around innovative technologies, the management of human resources, ICT-enabled business processes and sustainability; we predicted the latter would increasingly dominate our research agenda. All our strategic objectives have been achieved, leading to considerable growth in activity (Table 1), global leadership and policy influence (section e). Our research spend has grown considerably to over £17.8m (REF4), as has our industrial leverage (cash contributions of over £2.2m). Our downstream impact, via Knowledge Transfer Programmes, Technology Strategy Board projects and Royal Society feasibility funding, has also grown to over £1.2m. This activity has led to a significant growth in academic outputs, as well as 48 industry standards, guidance and policy documents.

Assessment Period	Research Spend per annum	Journal Papers per annum	PhDs/EngDs per annum	Staff Return (FTE)
RAE96	£665,648	16	7	14
RAE01	£1,184,820	31	8	13
RAE08	£1,577,150	65	12	27
REF14	£3,569,698	72 (432 total)	14.5	32.2

Table 1: Summary of annual research income, output and postgraduate activity

Our strategic goal is to *reinforce our global reputation for integrated built environment research to enable a high performance industry, a more sustainable built environment, and a healthier, more secure society*. Our research themes have evolved into integrated research programmes that respond to emerging agendas and opportunities, and engender the collaborative culture necessary to tackle technological, process and social challenges confronting the built environment, its organisations and professions. Our success has resulted in LU adopting '*Energy'* and '*Changing Environments and Infrastructure'* as two of its six institutional research challenge themes, both led by senior School staff ensuring that future capital investments and PhD studentships will be

prioritised to the Unit's themes over the next five years.

A crucial part of our strategy is the creation of a new centre to unify the research and enterprise of the School's two Units (C16 and B14). The ***Loughborough Centre for a Sustainable Built Environment (LCSBE)*** will be part-funded by industry, and represents a unique collaboration between our researchers, leading design and construction organisations, professional and regulatory bodies, construction clients and facility operators. Building on our multiple networks (section e), our status as a *Royal Academy of Engineering Centre of Excellence in Sustainable Building Design* and the opportunities afforded by LU's new London campus, this new centre of excellence will offer research projects, industry-based doctorates, consultancy and research-informed training in sustainable buildings and infrastructure. LCSBE will ensure the downstream impact of our work, and support fresh, user-informed upstream activity via a diverse range of funding opportunities. The concept of the Centre has attracted considerable support and interest from our network of industrial collaborators.

Theme 1: Building Energy Demand

Our Building Energy Demand research has a 42 year history and has expanded with 7 new appointments since RAE2008. It focuses on measurement and modelling to produce healthy, high quality indoor environments, with lower energy demand and CO_2 emissions. Since 2008, 41 externally funded projects have been completed and the current grant portfolio of 15 projects is valued at over £7.3m. Over the next five years, research will be organised into two allied sub-themes and grow as our newest staff (*Allinson*, *Hopfe*, *Mardaljevic*, *Taylor*) build their research portfolios.

1A Performance Measurement and Building Physics *(Lomas – academic lead)* addresses the creation and exploitation of: building energy databases; sensors and controls for managing building energy; and building energy technologies. All areas build on a substantial portfolio of prior work.

The creation of large, coherent datasets will enable better understanding of the socio-technical aspects of energy use in dwellings. Such knowledge informs government built environment energy policy, helps identify dwellings that would benefit from refurbishment, and helps quantify the risks created by extreme climate events. Database and analysis tools will build on the data and knowledge gained through monitoring, questionnaires and surveys conducted since 2008, most notably in three national, regional and city-scale multi-disciplinary and multi-partner EPSRC projects: CaRB '*Carbon Reduction in Buildings'* and 4M, '*Measurement, Modelling, Mapping and Management*' (£545k *Lomas*, *Firth*); and SECURE '*Self Conserving Urban Environments'* project (£476k *Lomas*, *Wright*, *Firth*, *Taylor*). Data from over 1000 homes has been used to advise the Department of Energy and Climate Change through a commissioned report '*How Trends in Appliances Affects Domestic CO_2 Emissions*' (*Lomas*) and contributions to the last three versions of the annual GB Housing Energy Fact File (*Lomas*, *Firth*, *Allinson*). In the next 5 years the database will grow as new, reliable, low-cost, wireless, sensor technologies are deployed to measure energy demands, internal temperatures and occupant behaviour. These data will provide a platform for numerous future research initiatives and for PhD and Masters level projects. The research will assist local and regional authorities and organisations interested in capitalising on the Government's Green Deal initiative. It will be the UK's most significant evidence base for the creation, verification and validation of building energy and environment models of individual homes and housing stocks.

Ongoing research into novel and emerging ICT to manage energy and the internal built environment will expand and continue to produce visible outputs. The Unit hosts the largest concentration of EPSRC TEDDI/BuildTEDDI projects of any university, with three consortium projects exploring how digital technology can measure and control domestic energy demand: '*Low Effort Energy Demand Reduction'* (£1.4m *Buswell*) seeks to link life-style to energy demand via pioneering sensory ethnography; '*Personalised Retrofit Decision Support Tools for UK Homes using Smart Home Technology*', (£525k *Firth*, *Hassan*) is studying smart homes to accelerate the uptake of domestic retrofits; whilst '*Digital Energy Feedback and Control Technology Optimisation*' (DEFACTO) (£1.2m *Lomas*, *Loveday*, *Allinson*) will implement a large-scale, 5-year, nationwide technology trial. The Unit has recently become joint co-ordinator of the EPSRC research network seeking to maximise the impacts of the whole EPSRC TEDDI/BuildTEDDI programme (£288k *Firth*, *Buswell*, *Hassan*).

We will continue to expand our work on building energy efficiency technologies capitalising on the success of the EPSRC-funded project, CALEBRE, '*Consumer-Appealing Low Energy technologies for Building Retrofitting*' (£313k *Loveday*) and our new work funded by Kingfisher, Europe's largest home DIY retailer (*Lomas*, *Loveday*) – see REF3a. These projects focus on the dynamics of domestic heating energy demand, occupant behaviour and comfort. Four full-scale test houses of different age and construction type have been acquired and are being characterised and equipped with simulated occupancy. The homes enable field testing of new heating controls, insulation systems and building-integrated low and renewable energy systems. New laboratory space has also been created to enable the testing of energy efficiency products, monitoring systems and management technologies. This collection of facilities is unique in the UK.

1B Modelling and Optimisation *(Wright – academic lead*) will expand in the areas of advanced computational fluid dynamics (CFD), daylight and photobiology, and optimisation. Since 2012, our modelling work has experienced a step change in its capacity to address large-scale, complex problems with the opening of High Performance Computing (HPC) Midlands, a 3000-core supercomputer that enables more adventurous and far-reaching modelling and optimization research (EPSRC, £1.24m *Cook*). Large Eddy Simulation (LES) modelling of offshore wind farms (E.ON, £98k *Cook*) has been completed. Work underway includes CFD using LES to predict buoyancy-driven natural ventilation in buildings, with the verification of results using measurements in our large salt water analogue facility (built in 2010). The HPC facility will also permit continuance of our thermal comfort modelling work, which has already led to one the world's first fully coupled thermal comfort and CFD models (£71k *Cook*). This work received follow-on funding from the EPSRC (£36k *Cook*) and now forms the basis of collaboration with researchers in Germany, China and the University of California Berkeley. Our new colleague *Hopfe*'s work will help bridge the gap between predicted and actual building performance (linking also to our work under Theme 2A).

Optimisation research will continue in a number of areas. For example, new HVAC software for designing lower energy buildings, will shortly be launched by *Integrated Environmental Solutions* (TSB, £181k *Wright*). Research using multi-objective optimisation techniques is being applied in the SECURE project to identify optimal strategies for housing refurbishment. Work to predict the long-term accurate provision of daylight founded on climate data (*Mardaljevic*) now forms the basis of the Priority Schools Building Programme design guide. This work will expand over the next five years to include photobiology related studies investigating the prediction of the non-visual effects of daylight on health, well-being and productivity. We will also bring our optimization, CFD and comfort modelling work to bear upon improving healthcare facilities. Monitoring and modelling of over 120 wards, operational areas and circulation spaces has already been undertaken as part of the *Design and Delivery of Robust Hospital Environments in a Changing Climate* project, (£285k *Lomas*). Future research will use these analyses to deliver a safer and healthier patient environment that promotes healing through improved indoor air quality, thermal comfort and daylight provision with reduced and well-controlled energy use.

The expansion of both sub-themes will be aided by the supply of PhD students funded through the LoLo Centre (recently extended for a further eight years). Dissemination and pathways to impact will be through the Centre's 32 partners, LCSBE's wider industrial membership (see above) and through the many international research networks of which staff are members, such as the European Energy Research Alliance Smart Cities initiative; *Buswell* is UK national coordinator.

Theme 2: Construction Technology and Organisation

We have the UK's longest-established research group specialising in the efficiency and performance of construction processes, products and organisations. We have delivered 209 externally funded projects since 2008, valued at £12.5m. This provides an excellent platform, supported by the LCSBE, for our staff, including the recently appointed *Adamu*, *Anvuur*, *Fernie*, *Soetanto*, *Thomson* and *Tuuli*, to develop our two sub-themes over the next five years.

2A Products and Processes *(Austin – academic lead)* focuses on improving how buildings and their components are designed, manufactured and deployed to reduce resource consumption and enhance their performance. In recent years this has been underpinned by the development of innovative ICT applications, process models and supply chain reconfiguration techniques to systematically address sequencing, automation and waste reduction, along with the development of novel materials and construction processes. Much of this work is founded on the legacy of the

Innovative Manufacturing and Construction Research Centre, the largest of the EPSRC's flagship innovative manufacturing research centres (EPSRC, £972k in the REF period). Our *'Freeform'* project (EPSRC, £1.27m *Austin*, *Buswell*, *Thorpe*) is scaling additive manufacturing technologies for construction, integrating expertise in cementitious materials, polymers and automation to create novel large-scale 3D printing processes. Having produced the world's first doubly curved printed concrete components, current research is developing a robotic system to create a radical, mould-free, manufacturing technology (PCT patent application GB 1118807.5). Future research will extend the process to incorporate textile reinforcement, novel admixtures and composite printing.

Over the next five years our research in designing, creating and managing the transition to a low carbon built environment will be expanded and integrated with our work in building energy demand. For example, our expertise in ICT is finding new problem domains in low carbon construction through our leadership of the *REViSITE project* (EC, £323k *Hassan*, *Firth*), which has shaped the EC 'Horizon 2020' funding agenda for ICT-related energy reduction research. The *Design4Energy project* (EC, £478k *Hassan*, *Firth*) will develop methods to predict the current and future energy efficiency of buildings to inform decisions around the optimisation of energy performance. A number of recently funded projects will explore management and procurement strategies for delivering zero-carbon and energy efficiency agendas. The *Bicester Eco-town Process Improvement Toolkit* project seeks to close the performance gap between predicted and real energy use in zero-carbon homes in the UK's largest zero-carbon development (TSB, £210k *Dainty*, *Thomson*, *Fernie*), while methods to accelerate and improve the take-up of housing retrofit solutions are being developed in the *Cooperation to Retrofit* project (TSB, £119k *Thomson*, *Fernie*). Socio-technical systems design work with TESCO (EPSRC, £197k *Dainty*, *Cook*) will trial integrated energy interventions across their store portfolio to reduce energy consumption. Our work on corporate social responsibility, founded on an EPSRC-funded network on responsible sourcing (EPSRC, £80k *Glass*), has nurtured a collaborative network of over 150 organisations developing novel material sourcing practices. This work will be taken forward through the new CORE project (EPSRC, £210k *Glass*) aimed at maximising stakeholder engagement in resource efficiency. Other work is developing new waste minimisation protocols that are being incorporated into the BS 8895 standard on material efficiency (EPSRC, TSB and industry, £130k *Osmani*).

Another strand of research is developing decision-support tools to inform the resilient design of critical built assets to natural and human-induced threats both now (EPSRC/EC, £495k *Bosher*) and for the future (EPSRC, £215k *Dainty*). Recent appointment *Soetanto* brings expertise in strategies for building community resilience through better designed built environments. Work in this area also capitalises on our co-location with UoA B14 staff, with whom we are working to deliver infrastructure systems resilient to climate change and malevolent acts such as terrorism.

Our expanding ICT research portfolio will focus on the novel application of Building Information Modelling (BIM). Building on our experience of mobile communications (EPSRC, £82k *Thorpe*, *Carrillo*) and working in collaboration with key industry networks COMIT and FIATECH, we are developing novel Field-BIM applications for Crossrail. Our recent appointment *Adamu* is exploring the use of augmented reality as a conduit for on-demand BIM content during construction, renovation and maintenance processes, and we have an established programme of work interrogating BIM for claims forensics (EPSRC, £107k *Emmitt*, *Ruikar*, *Lord*). Future work will explore the application of BIM for collaborative design and to manage construction information and the new modes of working required to support BIM-enabled environments (initially as part of work supported by Leverhulme, £16k *Demian*; and HEA, £44k *Soetanto*, *Adamu*). In addition, a new strand of work will involve collaborations with our Geomatics group (UoA B14) to develop cross-cutting approaches to 'Cyber-Physical Systems'. We are investing £150k in a Computer-Aided Facilities Management laboratory to extend the impact of BIM into building operation and management. This will integrate with our 3D printing research to exploit the linkage of virtual models and physical components for monitoring, control and manufacture. It will extend the application of BIM beyond design and construction into asset management and retrofit of building stocks to reduce energy demand. This will capitalise on large datasets captured from smart, instrumented infrastructure, linking to work in modelling and optimisation (submitted to UoA B14).

2B Projects and Organisation *(Gibb – academic lead)* responds to concerns over industry competitiveness and performance by supporting the delivery of sustainable, high value projects, via a healthy, knowledge-based workforce. Our current portfolio continues to develop theory and

practice of project organisation and industry performance in collaboration with our extensive industry and policy networks (Section e).

In line with our RAE2008 aspirations, our research has continued to reach beyond the improvement of built assets to address the performance and wellbeing of people that work in the sector. For example, our continuing work in occupational safety and health is developing new understandings of how to manage safety and health in construction, supported by funding from the Health and Safety Executive, Institution of Civil Engineers (ICE), Construction Skills, Construction Industry Research and Information Association (CIRIA) and the Institute of Occupational Safety & Health (IOSH) (£636k *Gibb*, *Dainty*). Research on vulnerable constituencies such as ageing and migrant workers (RCUK and ICE, £107k *Gibb*, *Dainty*) has led to high-profile research commissions including the '*Preconditioning for Success*' review of the construction of the London 2012 Olympic Park. Lawrence Waterman, head of Occupational Safety and Health for the ODA, is a visiting professor working with the team to develop tools for major infrastructure projects and to explore health implications of nano technologies in construction (IOSH, £131k *Gibb*).

A concurrent focus is on new business models for the delivery of high-value built asset solutions. Building on the *Knowledge and Immortal Information* project (EPSRC, £141k *Austin*, *Dainty*) and *Carrillo*'s work on knowledge capture and re-use (EPSRC, £49k), we are developing new processes and systems for delivering performance-based buildings and infrastructure. For example, demands for alternative models of healthcare facilities procurement have been addressed through our contributions to the HaCIRIC research centre (EPSRC, £2.3m *Price*, *Austin*, *Demian*, *Glass*, *Thomson*). This research will be taken forward via ongoing collaborative work with the Department of Health (DH, £338k) supported by Impact Acceleration Account funding (IAA, £97k *Price*).

A third priority for the sub-theme will be to consolidate our prominent position in analysing and shaping industry reform agendas. This work will be led by *Fernie* and *Fellows*, both of whom have coordinated CIB working commissions on cultural change and sector reform, as well as a related ESRC-funded seminar series (£18k *Fellows*). Our recent appointments, *Anvuur*, *Lord*, *Thomson* and *Tuuli*, are all working in the organisation and delivery of complex, high value projects. They will consolidate our work with the Olympics legacy organisation, Crossrail, the new nuclear build programme, and the Thames Tideway projects to build an expanded portfolio of work on project performance, safety and resilience. *Gibb* has recently been appointed to the RAEng chair of Complex Projects and will lead activity in this area.

c. People:

Our Unit recognises that the aggregation of leading researchers in a world-class research environment is a prerequisite for delivering high-impact research. Our staffing strategy focuses on the recruitment of staff with international reputations or exceptional research promise and the creation of an environment that supports and encourages their intellectual growth. We align our capital investment in research facilities to provide the infrastructure necessary for staff to develop their research to the highest possible level.

i. Staffing strategy and staff development

Since 2008 we have grown the Unit's research active staff complement by 16%. Eight staff have left the Unit with two retiring (both remain emeritus professors), and the remainder taking up senior positions in other institutions. The recruitment of replacements, and additional investment, has allowed us to reinvigorate the Unit's expertise in ways that better align with our research themes. Four professors (*Cook*, *Fellows*, *Lomas* and *Mardaljevic*), three senior lecturers (*Anvuur*, *Fernie* and *Firth*), seven lecturers (*Adamu*, *Hopfe*, *Lord*, *Soetanto*, *Taylor*, *Thomson* and *Tuuli*) and one research fellow (*Allinson*) have been recruited to strengthen research capacity and capabilities. Consistent with our RAE2008 strategy, seven of these staff have been recruited to take forward our *Building Energy Demand* research portfolio: *Lomas* has brought strategic direction in building performance measurement and modelling; *Cook*, *Mardaljevic*, *Hopfe* and *Firth* have broadened our modelling expertise to include ventilation, daylight and building stocks and *Allinson* strengthens the expertise in building physics and experimental research, as has the appointment of RAEng/CIBSE Visiting Professor Woolf. The *Construction Technology and Organisation* theme has been strengthened in the area of commercial management with the appointments of *Anvuur*, *Fellows*,

Lord, *Thomson* and *Tuuli*, while *Fernie* now leads work on industry reform. *Adamu* contributes to our work in both BIM and building energy, and *Soetanto* to our BIM, socio-technical systems and resilience portfolio. All academic staff are appointed on open-ended contracts.

We augment our expertise through our visiting professors, who also provide connectivity to international networks and centres of excellence (Anumba (Penn State), Augenbroe (Georgia Tech), Ballard (Berkeley), Cozzens (Georgia Tech), Fang (Tsinghua), Loosemore (UNSW), Matsumura (Tokyo)) and policy connectivity (Holmes (Arup), Oliver (BG Group), Porritt, Waterman (ODA), Woolf (Hoare Lea) and Jones (E.ON)). We have a well-stratified staff complement which represents all stages of development; the median age of staff returned is 50 with one likely retirement within 5 years, providing an excellent platform for delivering our objectives and for succession.

New staff are provided with a fully-funded research studentship and capital funds of £15k. Additional funds are made available for travel, conferences and networking. We have robust policies for supporting the development of all staff, and a specific staff development system for probationary (early career) staff. This restricts probationers' teaching and administration duties significantly for three years (to 33, 50 and 66% load) during which time they are advised by a senior staff member who helps develop their research. Research performance is a priority and all academic staff submit an annual Personal Research Plan, which facilitates discussions of development needs, satisfied through our staff development programme (accredited by the Institute of Leadership and Management). This process embeds research in our performance monitoring and reward systems, overseen by the University's Research Performance Monitoring Committee. The Research Office provides bespoke one-to-one support to staff writing grant proposals. The most promising early career researchers may be selected to participate in the *Developing Future Research Leaders* programme, an initiative that provides dedicated coaching, action learning and 360° feedback to selected participants (*Tuuli* is participating in this scheme). Mid-career academics with exceptional research promise may be selected to join LU's highly selective LEADER programme, which, through development initiatives and special projects, supports participants towards achieving chairs (*Cook* was selected in 2013).

Perhaps the best demonstration of the effectiveness of our staff development approach, and our policy of promoting and retaining those demonstrating a sustained record of research excellence, is the evidence of our staff promotions since RAE2008. *Bosher*, *Buswell*, *Demian*, *Firth*, *Ruikar* and *Osmani* have become senior lecturers having met robust institutional criteria, while *Cook*, *Glass* and *Hassan* have been awarded personal chairs after stringent external verification of their research profile. *Taylor* and *Adamu* have been awarded academic posts having worked as research associates within the Unit. Furthermore, *Gibb*, *Glass* and *Lomas* have undertaken extended secondment and sabbatical periods at RMIT, the Pre-cast Concrete Association and Cambridge University respectively. *Loveday* and *Gibb* have both held RAEng chairs (co-sponsored by E.ON and ECI respectively) within the REF period. *Lomas* has been awarded a Leverhulme Research Fellowship (£29k) and *Tuuli* a fellowship from the National Natural Science Foundation of China (£15k). Within the REF period staff have held 16 visiting professorships or fellowships including: Aachen, Germany (*Austin*, *Buswell*); Chongqing, China (*Tuuli*); Chalmers, Sweden (*Dainty*); BUE, Egypt (*Hassan*); Hong Kong (*Fellows*, *Thorpe*, *Tuuli*); UNSW, Australia (*Dainty*); RMIT, Australia (*Gibb*); Ryerson, Canada (*Soetanto*); and Tianjin, China (*Fellows*).

In 2010, LU implemented a plan to support the career development of researchers in line with the Concordat, receiving the EC's HR Excellence in Research Award. The plan (updated in 2012) includes commitment to a University-wide research staff mentoring scheme, a revised code of practice for the employment of researchers, and the establishment of the LU Research Staff Association (chaired by two research associates from this Unit). LU seeks to achieve equality for all, including mandatory recruitment and selection training, and is committed to Athena SWAN. It is a Bronze award holder and the School will apply for Silver in April 2014. In support of this, our School is engaged in an EC FP7-funded action research programme to implement good practice in providing equal opportunities for female staff (*Hassan*, *Dainty*). Consistent with LU policy, the Unit expects high standards of research integrity and ethics (overseen by *Thomson*). The University has an Ethics Committee and a Research Misconduct and Whistle-Blowing Policy to ensure that research integrity is maintained.

ii. Research students

Since 2008, the Unit has been awarded 91 PhD and EngD studentships, including a competitive Age UK and 6 EPSRC DTA studentships, and, importantly, 77 EPSRC students funded through research grants or our two Centres of Doctoral Training (CDTs), the LoLo Centre and the CICE. The School has 198 co-located full-time doctoral students along with 34 research associates.

We provide a rich training environment for all of our research students, along with excellent facilities and support. All returned staff contribute to our doctoral training programmes, delivering mentoring and supervision and a cohort-based experience. Each student has two academic supervisors and a director of research programme; many students also have an industrial mentor. Progress is monitored through regular supervisory meetings and a robust academic progress review conducted at the end of each year by an independent examiner. Overall quality is assured by quarterly progress review boards chaired by the Associate Dean Research (ADR).

All students are provided with a laptop, access to our laboratory facilities, technician support and funds for travel and conference attendance. The LU Graduate School provides transferable and employability training to meet the requirements of the researcher development framework. This includes face-to-face workshops, an annual research conference including poster competition and the 'Café Academique' forum where PhD students can debate the latest ideas from all areas of research. Our research hub facilitates peer-to-peer learning between students from diverse academic backgrounds and students benefit from the School's extensive seminar programme (23 visiting speakers since 2010), quarterly doctoral seminar programme and annual away days.

Our two CDTs ensure a critical mass of students. The CICE (EPSRC, £5.83m) was established in April 1999 and, since 2008, has supported 44 innovative EngD research projects in partnership with 33 sponsoring companies spanning the built environment sector. The LoLo Centre (EPSRC, £5.81m), is a partnership between UCL and LU and has supported 20 PhD projects at LU.

The CDTs set the template for our future PhD training ambitions. University studentships will be aligned with LU's six research challenges, which include Energy and Infrastructure (see above). At Unit level, students will be clustered around our four research sub-themes, with many straddling more than one. This will create the critical mass of underpinning endeavour needed to drive the Unit's future ambitions. It will also align PhD students with our major research projects and resources, expose them to world-class research programmes, and provide the gateway to experiencing interdisciplinary, multi-institution work in leading UK and overseas institutions. The aim is to stimulate our students, broaden their horizons, and deepen their knowledge in order to mould the built environment research leaders of tomorrow.

d. Income, infrastructure and facilities

Research funding: Income has grown over the REF period to more than £17.8m comprising funding from the UK research councils (£13.4m), EC (£902k), industry (£2m), Government (£348k) charities (£622k) and other funding agencies (£577k). We have also generated over £1m in consultancy income, mostly for technology transfer activities. Virtually all external funding, won through open competition, involves external collaboration. Significant grants include: the renewal of the *CICE EngD centre* (£5.83m); winning the *Lo-Lo Centre for Doctoral Research* (£5.81m); the *IMCRC* (£972k within the REF period), the largest EPSRC innovative manufacturing research centre; the *HaCIRIC Centre* (£2.3m), developing new approaches to delivering effective healthcare infrastructure in collaboration with Imperial College, Salford and Reading; the *Sustainable Urban Environment* (SUE) portfolio comprising the '4M' (£545k) and *SECURE* projects (£476k) – multi-institutional investigations of the urban carbon footprint of Leicester and the energy demands of the North East region – and the *SUE MoT* project (£167k) that developed tools for evaluating socio-economic impacts of development; the LU *TEDDI/BuildTEDDI portfolio* (£3.4m), the largest concentration of such projects aiming for a step-change reduction in energy use in homes; *Freeform's* (£1.09m) development of mega-scale 3D concrete printing processes for construction, with a follow-on EPSRC KTA (£178k with Hyundai, Fosters and Buro Happold) and a new confidential collaboration to commercialise the approach; the *EC portfolio of six projects in energy efficiency and intelligent building systems* (£1.25m); the *Institute of Safety and Health* competitive programme (£365k) exploring safety knowledge in hazardous, highly networked sectors; and the two *RAEng sponsored chairs* in collaboration with E.ON (£578k) and the ECI (£589k). We have

also been awarded a RAEng visiting professorship in Low Carbon Construction (£100k).

Funding Strategies: The Unit's grant income strategy is founded upon the recruitment of, and investment in, high performing staff, coupled to our emphasis on collaborative and interdisciplinary working. We build unique capabilities which align with funding programmes by mobilising interdisciplinary teams around the needs of funding calls. Invariably these also demand inputs from colleagues from other disciplines; the LU research challenges facilitate this.

Demand-managed calls are led by the LU Research Office, which coalesces multiple Units where appropriate. Our sub-theme leaders (*Lomas*, *Wright*, *Austin* and *Gibb*) sit on the School Research Committee along with the Directors of our three research centres. This is chaired by the ADR, who sits on the University Research Committee, thus aligning the Unit's activities with University research strategy and promoting collaborative research with other schools. The School has a full-time Research Manager who oversees and supports all funding applications through to submission and plays a vital role in filtering and channelling key information about funding opportunities.

A percentage of overheads from each research project is distributed to the investigators to pump-prime future research. Over the next five years funds to stimulate new research will also be provided by the new LCSBE. This agile yet coordinated approach to exploiting emerging funding opportunities and driving new research agendas will enable us to refresh and intensify our research activity in line with our stakeholders' needs.

Infrastructure and Facilities: We invest in our infrastructure and facilities in line with our funding priorities and staff requirements. Our 'Research Hub' comprises a 1000m^2 award-winning open-plan space, providing a flexible working environment for research staff and students. This is supplemented by our ICT systems (supported by two dedicated School IT staff) and the adjacent recently-refurbished university library. Our 3000m^2 of specialist laboratory space, supported by 13 technical staff, has been refurbished since 2008 with a robotic arm facility to support our Freeform 3D concrete printing facility (£101k) and improvements in building energy research facilities (totalling over £798k). The latter was funded by the Research Councils Infrastructure Fund, School funds, the EPSRC CDT, the National House Building Council, the Building Research Establishment (BRE) and industry (the Kingfisher Group). New facilities include two laboratories (168m^2), four test houses, a solar simulator, a daylighting suite and a fluids laboratory (including a large brine facility for modelling buoyancy-driven natural ventilation). The test houses are furnished with state-of-the-art environmental monitoring equipment and systems to simulate occupants' use of lights, appliances, internal doors, windows and blinds. We have also purchased an air source heat pump with solar thermal rig and energy store, a domestic central heating rig, a large environmental chamber for thermal comfort and indoor air quality research, equipment for testing and calibrating electrical power, temperature and RH sensors and over £390k of equipment for field testing the performance of domestic and non-domestic buildings. Finally, two EPSRC grants totalling £1.24m have enabled the commissioning of one of the fastest high performance computing clusters in the UK. This is being used by the Unit to support accurate air flow modelling.

e. Collaboration or contribution to the discipline or research base

We pride ourselves on our interdisciplinary approach to addressing real-world problems in the built environment through academically rigorous research. To this end we collaborate extensively with colleagues from a range of disciplines, both within and outside LU, drawing upon our extensive networks of research partners developed through our membership and leadership of national and international fora. By co-producing knowledge with our partners we create impact pathways for our research and shape industry agendas rather than merely responding to them.

Interdisciplinary research - Together with B14, staff represent every major discipline associated with the built environment: civil and structural engineering, water and hydraulics, materials science, geotechnics, land surveying and geomatics, transport studies, quantity surveying, architecture, construction management, building services engineering and building physics. We adopt a problem-driven approach to our work whereby expertise is mobilised in response to the intellectual challenges that we confront, rather than being kept within disciplinary silos. Necessarily, this approach extends into our cross-school collaborations, themselves supported by LU's cross-cutting research challenges through which interdisciplinary groups are brought together around research challenges and funding calls. Over 50% of the Unit's funded portfolio involves inter-school

collaboration, currently involving externally funded projects with the Schools of Design, Electronic, Electrical and Systems Engineering, Science, Business and Economics, Mechanical and Manufacturing Engineering, Aeronautical, Automotive, Chemical and Materials Engineering, and Social, Geographical and Political Sciences.

Networks and clusters – Our collaborative approach embodies extensive engagement with industry. The *ECI*, Europe's only trans-national network of excellence in engineering construction, brings together 40 of the most innovative clients, contractors, specialists and support organisations managed within dedicated taskforces, all involving Unit staff. These are a conduit for international collaboration, technology transfer and informing our research direction. The Unit has also been responsible for forming and/or leading influential research networks such as the *COMIT* industry network (effective use of Mobile IT in the construction industry, *Thorpe*) and the EPSRC-funded *APRES* network on responsible sourcing (*Glass*). We also have prominent roles in the *Fire Protection Association* (*Ruikar*), *Age-UK* (*Gibb*), *Airport Energy Technologies Network* (*Eftekhari*), *CIB* (see below), *International Building Performance and Simulation Association* (*Cook*, *Wright*) and industry organisations *BSIRIA* (*Hassan*), *CIRIA* (*Osmani*), *CIBSE*, *ASHRAE* (*Wright*, *Cook*) and *BRE* (*Glass*). *Austin* was the sole academic contributor to the *Constructing Excellence* 'Never Waste a Good Crisis' report that critically examined the industry's resistance to reform agendas.

National and international research collaborations – We have 45 on-going engagements with overseas universities and research institutions from 18 countries, and numerous domestic links. We have hosted 94 residential academic visitors from 18 countries over the REF period. Our six EC projects involve 72 European partners from 24 countries. The success of these collaborations is demonstrated by their longevity (e.g. Cambridge 27 years, Stanford 23 years, UNSW and Hong Kong over 20 years, MIT, and Georgia Tech 10 years) and the number of joint outputs produced over the REF period (over 200 journal papers authored with academics from other institutions).

Seminars, journal editorships, conference activities and CPD – We have benefited from an ESRC-funded Seminar Series on *Cultural Issues for Project Organisations* (ESRC, £18k *Fellows*) that attracted international speakers from across the world. Seven high quality peer-reviewed journals have been edited by staff during the REF period: *Building and Environment* (*Wright*), *Construction Management and Economics* (*Dainty*), *Energy & Buildings* (*Mardaljevic*), *ITCon* (*Ruikar*), *Built Environment Project and Asset Management* (*Hassan), Building Research and Innovation* (*Lomas*) and *Engineering Construction and Architectural Management* (*Thorpe*, *Thomson*). Unit staff sit on the editorial boards of over 30 international journals, have received 34 keynote invitations and chaired over 20 international conferences, including the *International Conference on Building Simulation and Optimization*, initiated and hosted by Unit staff in 2012 (*Wright*, *Cook*). Staff deliver a wide range of research-based CPD e.g. 16 events for the Association for Project Safety delivered to 400 occupational safety and health professionals (*Gibb*), the ICE Thomas Telford 3-day design management courses to 161 delegates (*Austin*); and training for the Association of Chief Police Officers for 240 counter terrorism advisors (*Bosher*).

Professional associations and learned societies – Most of the Unit's staff are members of one or more of the built environment professional institutions, and/or play a significant role in shaping research and development agendas within such bodies. For example, *Carrillo* sits on the *CIOB*'s Research and Innovation panel, *Dainty* on the *ConstructionSkills* Technical Reference Group, *Glass* is a *BRE* Trust Fellow and *Thomson* sits on the Editorial Committee for the *RICS Foundation*. The Unit plays a particularly prominent role in the *CIB* having led seven high profile commissions over the REF period (*Bosher* TG63, *Dainty* TG76, *Emmitt* W96, *Fellows* W112, *Fernie* TG84, *Gibb* W99, *Ruikar* TG83). *Bosher* also advises the *United Nations* International Strategy for Disaster Reduction and *Loveday* chairs *ASHRAE*'s Technical Committee TC2.1 (Physiology and Human Environment). Our excellence in sustainability has been recognised by the *RAEng* who have designated us a *Centre of Excellence in Sustainable Building Design*.

PGR training – The Unit has several reciprocal agreements with international collaborating institutions for PGR student exchange programmes, currently funding secondments to TU Delft, National Technical University of Athens, Oklahoma State, Penn State, Stanford and UC Berkley.

Other contributions to the discipline – The Unit contributes 10 members to EPSRC grant assessment panels as well as members of the peer review college. In addition colleagues have acted as external examiners to 111 PhD students over the REF period.