UNIVERSITY OF CAMBRIDGE

LAING O'ROURKE CENTRE *for* CONSTRUCTION ENGINEERING *and* TECHNOLOGY

Transforming Construction

10 YEARS

Celebrating 10 years of the Laing O'Rourke Centre for Construction Engineering and Technology at the University of Cambridge Department of Engineering. The Centre was launched in 2010 with industry partner Laing O'Rourke to fulfil a shared vision of transforming the construction industry through **innovation, education and technology**.

Our vision and mission

Vision:

Our vision is to improve the quality of life for all in an equitable and sustainable way.

Mission:

The Laing O'Rourke Centre for Construction Engineering and Technology aims to drive transformation in the construction industry by focusing on three core pillars:

Education and Skills

Educate and inspire emerging industry leaders and innovators.

Research and Innovation

Deliver world-class, innovative research to drive change.

Thought Leadership and Policy

Deliver evidence-based research and thought leadership to underpin policy.

Contents

Testimonials

We need people, processes and research to deliver fresh and rigorous thinking and thinkers to lead the changes needed to create a construction industry ready to maximise the prospects that new technology, modular construction and digitalisation offer. These are very exciting times for engineering and construction but the industry must learn to procure for better and long-term value, innovate and upskill to ensure UK construction fulfils its world-class capabilities.

The Laing O'Rourke Centre for Construction Engineering and Technology brings the high-level thinking, industry-informed research and executive education that will drive transformation and inform leadership to enable UK construction to lead the field.

Professor Peter Hansford CBE FREng FICE FAPM FRSA

Honorary Professor and former Chair of Construction and Infrastructure Policy at the Bartlett School of Construction and Project Management, University College London

Prof. Hansford has served as Chief Construction Adviser to the UK Government and President of the Institution of Civil Engineers

Ten years ago, at the launch of the Laing O'Rourke Centre for Construction Engineering and Technology, I was excited by the Centre's aspiration to be a catalyst for change in the construction industry. I have followed its development with much interest ever since. It is great to celebrate this 10-year anniversary, not only because of how much has been achieved, but because the Centre's success enables ambitious plans for the future.

Professor Dame Ann Dowling OM DBE FRS FREng

Deputy Vice-Chancellor and Emeritus Professor of Mechanical Engineering, University of Cambridge; President of the Royal Academy of Engineering 2014-19; Head of the Department of Engineering, University of Cambridge 2009-14

Executive summary

Since its inception nearly 10 years ago, the Laing O'Rourke Centre at the University of Cambridge, in collaboration with our strategic industry partner Laing O'Rourke, has focused on delivering transformation in the construction sector. We have worked towards this goal by establishing and expanding our highly successful advanced leadership Construction Engineering Master's degree programme, building a portfolio of collaborative research projects linked directly to industry challenges and pursuing research aimed at generating an evidence base to inform key policy decisions in government and industry.

Our 10th anniversary comes at a pivotal time for the industry. The fourth industrial revolution brings unprecedented opportunities to modernise construction through the exploitation of information and new technologies that can inform and underpin better decision-making to help shape society and improve the quality of life in an equitable and sustainable way. We live in a challenging world where climate change and gaps in social equality threaten future global security and the wellbeing of all. We must strive to deliver a more productive and greener industry that can address these challenges and provide benefits such as energy-efficient affordable homes, smart and resilient infrastructure, lower emissions, and cleaner water and air, which will enrich cities and communities throughout the UK and beyond.

The Laing O'Rourke Centre is working at the forefront of this revolution applying world-class research to digital engineering, offsite manufacturing and whole-life performance to boost productivity and secure enhanced performance through the development of smarter assets. Our strategic focus informs policy and aligns with the Construction Sector Deal that sets out government's plan to support, invest in and transform the sector for the greater good.

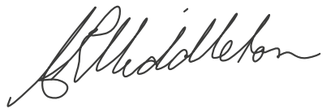
Implementing industry change at this scale requires vision and drive. Ray O'Rourke's foresight led to Laing O'Rourke joining with the Department of Engineering and Cambridge Judge Business School at the University of Cambridge to establish the Laing O'Rourke Centre in July 2010 to fulfil a shared vision of transforming the construction industry through pioneering research and by educating industry leaders of tomorrow. The Centre owes particular thanks to Ray O'Rourke for turning this vision into reality.

Our Construction Engineering Master's (CEM) multidisciplinary leadership programme offers professionals the opportunity to explore the future of the industry alongside leading government, business and academic experts. Our reputation continues to grow as industry acknowledges the power of this course to drive change, leading to an increasing number and range of professionals applying year on year and a growing cadre of alumni who are moving into leadership positions from which they can effect change and implement the knowledge learned on the CEM.

It has been a privilege to work with a truly exceptional team and I am very grateful for their commitment, talent and passion to focus on outcomes and "making it happen". Our team is committed to challenging the status quo and continually seeking better ways of tackling every aspect of our work.

Our unique strategic partnership with Laing O'Rourke demonstrates what can be achieved by a close industry-academic collaboration and I am excited by the opportunities ahead to increase our impact and influence as we strive to deliver the shared vision of transforming the construction industry.

I hope you find this milestone Report informative and exciting, and are inspired to join us to work together to deliver positive and impactful change in our industry.



Professor Campbell Middleton
Centre Director

The Centre

The Centre was launched in 2010 as a partnership between the University of Cambridge Department of Engineering, Cambridge Judge Business School and industry partner Laing O'Rourke, the UK's largest privately-owned construction company, to fulfil a shared vision of transforming the construction industry through innovation, education and technology.

Integrity, intellectual rigour, innovation and excellence provide our guiding principles and ethos. By harnessing the power of world-leading research and educational excellence, we aim to ensure evidence-based outputs influence policy and industry practice to the benefit of society.

This ambition is firmly within reach. The Centre's reputation continues to grow and we have established the foundations on which this ambition is being realised.

> *The Laing O'Rourke Centre for Construction Engineering and Technology is a brilliant idea for advancing construction. Companies on their own have tried to achieve advances in construction in the past, but resources and resulting benefits remained limited to an individual company. By investing in Cambridge, Laing O'Rourke is able to use the impartial setting of academia to engage academics and the best minds from leading engineering and construction companies to create knowledge, talent, systems and thought leadership to benefit the entire industry. I have remained engaged with the Centre and University since 2010, when I was the inaugural Laing O'Rourke Centre Distinguished Lecturer. I am extremely impressed with the critical thinking and creativity of the faculty and students at Cambridge.*
>
> William F. Baker, PE, SE, CEng, FASCE, FIStructE, NAE, FREng
>
> **Honorary Professor of Structural Engineering Design at the University of Cambridge; Consulting Partner, Skidmore, Owings & Merrill LLP, Chicago, USA**

Integrity

Intellectual rigour

Innovation

Excellence

Our identity and strategy

Our strategy

The Centre's strategy supports the ambitions of the Industrial Strategy Sector Deal for Construction (2018)[1] between government and industry, aimed at improving exports and reducing whole-life costs, project timescales and greenhouse gas emissions. Our world is facing unprecedented challenges as a result of global population growth, urbanisation, resource limitations and climate change. These pressures present challenge to the construction industry, but also opportunity to transform by developing innovative, efficient, sustainable solutions. The Centre aims to be at the vanguard of such a transformation. We are working with industry and policy makers to ensure the sector is fit for future purpose, delivering better-performing assets faster and at reduced cost while advancing construction and leadership skills.

The three pillars of our mission each play a key role in delivering the research and leadership that underpin transformation in construction.

Thought Leadership and Policy

Delivering evidence-based research to underpin policy and provide economic, social and environmental benefits to society.

The Centre contains a wealth of expertise and sector knowledge, as well as an ever-growing body of evidence-based research. Our reputation for excellence attracts engagement from accomplished professionals across academia, industry and organisations shaping construction policies and practice. This growing network of researchers, experts and decision-makers ensures that evidence-based research, innovative technologies, skills and leadership effectively underpin policy and deliver impact to industry and society.

[1] The 2018 Construction Sector Deal built on the Construction 2025 report published by the government and the Construction Leadership Council (CLC) in 2013.

Education and Skills

Educating leaders and innovators to transform the construction industry.

Central to the success of industry-wide transformation is the vision and leadership of stakeholders across the sector and a suitably skilled workforce. The Centre focuses on educating and inspiring current and emerging leaders and innovators, equipping them to influence the industry and implement research outputs that deliver value to society.

In 2011 the Centre launched a unique and now highly-acclaimed Construction Engineering Master's (CEM) degree at the University of Cambridge. This advanced leadership programme is designed to equip industry professionals with the skills and knowledge to become agents of change within their organisations and the construction sector as a whole.

Research and Innovation

Driving change by delivering world-class, innovative research.

Evidence-based research is conducted by Centre academics, students (Master's and PhD), post-doctoral researchers and specialist research groups securing large collaborative grants. Our research portfolio is directly aligned to the needs of the industry and places a strong emphasis on technology and innovation – covering all three of the strategic areas highlighted by the Construction Sector Deal (2018) as key for delivering transformative goals.

- **Digital techniques and technologies**
- **Offsite manufacturing**
- **Whole life asset performance**

The Centre's key accompanying research themes include:

Skills | Productivity | Procurement | Net-zero Carbon | Housing

Collaborate with us

Industry – academia – government cooperation

Industry, academia, government bodies and associated organisations can become strong allies in transforming the way infrastructure is designed, built and managed – together driving the innovation needed to achieve the Construction Sector Deal goals and secure associated benefits.

Collaboration is key to the success of the Centre's mission across all three pillars of our strategic framework.

Our CEM programme attracts emerging leaders from a wide range of commercial companies and is supported by leading figures from government, industry and academia.

We work with many of the most experienced and successful members of the construction sector to undertake research with direct applicability to industry and society.

The Centre works with various organisations to help shape policy through membership of and contribution to government and industry advisory panels, committees, summits and workshops.

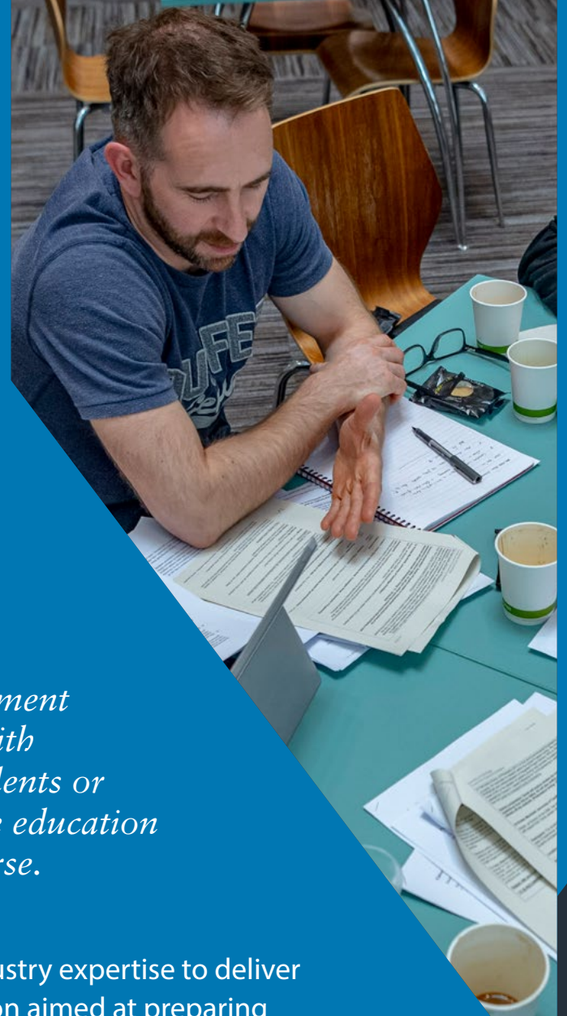
We welcome the opportunity to work with partners to enable sharing of research, outcomes, innovation, opportunities and ideas. Please contact us to discuss ways in which we might collaborate.

Professor Campbell Middleton

Centre Director

prof@construction.cam.ac.uk

Education and Skills



The Centre offers talent and skill development opportunities for the industry. Interact with exceptional University of Cambridge students or develop in-house talent through executive education or our acclaimed leadership Master's course.

Key to industry transformation is the development of talent, leadership and enhanced skillsets. The University of Cambridge attracts some of the best and brightest students, researchers and academics from the UK and around the world. Within this high-achieving setting, the Centre draws together both academic and industry expertise to deliver education aimed at preparing industry professionals to drive transformation in the industry.

Much of this educational work results not only in upskilling and the development of talent but also in the creation of evidence-based research aimed at solving industry problems, catalysing innovation and informing policy.

Explore
opportunities to get involved

Page 12

Engage
with university students, the Constructionarium

Page 13

Enroll
on the unique Construction Engineering Master's leadership degree

Page 14

Equipping and inspiring industry leaders

44

PhD and post-doctoral researchers educated

>120

Students completed the Constructionarium programme

180

Industry professionals educated through the Construction Engineering Master's degree

...representing

49

unique commercial companies*

*Organisations including: government; clients; consultants; contractors; supply chain partners; and technology providers

Benefit by getting involved

Industry involvement is key to our education activity and there are a number of ways for industry to engage with the Centre.

Access
emerging talent by engaging with high-calibre students

Companies can get involved in University of Cambridge Engineering recruitment days, facilitate a fourth-year student's research project or lend expertise to the Constructionarium programme (page 13) – a practical training exercise guiding students through all the stages of a construction project. Industry partners may also become involved in state-of-the-art research by sponsoring (or co-sponsoring) PhD students or post-doctoral researchers at the University of Cambridge.

Develop
talent and knowledge within your company

The Centre runs executive education courses to expose senior company personnel to cutting-edge technologies and innovations. These courses provide participants space to reflect on their businesses' activities, develop their knowledge and engage in discussion on emerging topics of concern or opportunity with relevant experts in the field.

Equip
your emerging leaders with the skills to effect real change in the industry

Central to the Centre's objectives has been the launch of a unique Construction Engineering Master's (CEM) degree programme designed for experienced industry professionals identified as emerging leaders in their company.

For more information, see page 14.

Constructionarium

Every year the Centre funds and facilitates the Constructionarium project for third-year undergraduate engineering students at the University of Cambridge. The Constructionarium provides an important opportunity to turn theory into practice as they receive first-hand experience building and managing a construction project.

Upskilling through experience

During the week-long Constructionarium, student teams construct small-scale replicas of iconic engineering projects, learning about project and people management by taking on management and labour roles. The students are involved in all aspects of planning and constructing their structures, from the preparation of a tender to temporary works designs, scheduling, budgeting, and contract reviews each evening with the client. They gain significant appreciation for the multi-faceted nature of the construction industry and considerations involved in delivering a finished product on time and to budget, while taking care of the environment and the health and safety of everyone on site.

Learning through industry-academia collaboration

Industry professionals donate their time and lend their expertise to supervise students throughout the planning, design and build stages – an invaluable learning experience for students. The project is carried out in conjunction with a construction partner, Laing O'Rourke, and civil engineering consultant, Ramboll. Additional technical support is provided by Trimble. The support and guidance from these professionals is crucial to the learning aims of Constructionarium.

Student response

Students return to University with with broadened horizons, practical knowledge, problem-solving skills and an appreciation for the importance of teamwork for successful project completion.

The value of the programme is acknowledged by both students and industry. In 2019 all supporting industry staff had themselves undertaken the Constructionarium as undergraduates, volunteering to participate once again and gaining further experience in a supervisory role.

Alumni Johannes Whittam, now the Rwanda Program Director at Bridges to Prosperity, describes the Constructionarium project as "one of the most educational and directly applicable parts of the course for me. For designers (like me) it's vital to be able to keep perspective on how easy a design will be to construct, and Constructionarium definitely gave me a head start in this respect".

The Constructionarium website shares the story of Cambridge alumni Benedict Langslow: "I would definitely recommend attending Constructionarium as it really opens your eyes to the breadth of roles available and as well as the practical experience it gives you great exposure to the industry and the chance to demonstrate your skills to potential employers." Benedict was invited to apply for a graduate role with Laing O'Rourke after they supported his week at Constructionarium.

Constructionarium website:
www.constructionarium.co.uk/

Construction Engineering Master's degree

The leadership programme for the construction industry

A note from the Course Director:

"This course is structured to not just benefit the participants but their organisations and the industry. Through combining the rigour of academic research with the maturity and industry insights of our participants, the CEM is positioned to support insightful research outputs.

There can be tensions between the worlds of academia and industry, but we are constantly trying to bridge these worlds. When done well it leads to significant value for all.

Dr Kristen MacAskill
CEM Course Director

The University of Cambridge Construction Engineering Master's (CEM) leadership degree equips business leaders to transform the construction industry.

The unique, multidisciplinary programme attracts professionals from a wide range of professions, companies and sectors – providing an opportunity for personal, professional and academic development, alongside the benefits of networking and learning from others on the course.

The CEM is a two-year, part-time Master of Studies (MSt) degree delivered by the Centre in collaboration with the Cambridge Judge Business School.

The programme is delivered by academic staff, government representatives and high-level industry experts representing a range of disciplines to ensure content is industry-focused and underpins strategic research priorities for the transformation of the industry. The programme covers the industry in its broadest sense, from policy and planning through to the physical construction and maintenance of infrastructure. Programme content is constantly evolving to keep pace with the changing landscape of the sector and continues to attract support from a growing network of practitioners, professional associations, industry leaders and government organisations.

The course aims to educate and inspire students to become agents of change through research and study as well as through professional and personal development, with an ongoing focus on communication, leadership and research skills. Feedback shows that CEM graduates return to their workplace with the skills, confidence and ability to play a transformative role in their companies and the wider industry.

During the programme, students also engage in informing and driving the industry's transformation agenda through research, discussion, thought leadership exercises and report writing.

For further details on thought leadership through the CEM, see page 48.

Engage with us

The degree is aimed at individuals with several years' professional experience who have been identified as current or emerging leaders in their field.

The format allows students to combine working and studying, inviting a synergy between real-time industry challenges and world-leading research to fully explore and consider potential solutions. Students come from a variety of companies and organisations and hold a number of senior roles across design, construction, project management, facilities management, law and financial management.

Please get in touch to discuss how you or your employees can join, and benefit from, this unique programme.

Contact our Centre Manager at:

centre.manager@construction.cam.ac.uk
Telephone: +44 (0)1223 332812
Website: www.construction.cam.ac.uk/cem-programme

Construction Engineering Master's degree

The leadership programme for the construction industry

In just one year (Dec '18 – Nov '19):

96

Experts taught on the CEM programme*

*Excluding Centre staff and academics

29
From industry

54
From academia

13
From government

Testimonials from students and alumni

I believe this course is not only unique but vital for our industry.

Just when you think you know how the industry works and what is best, this course gets you to question, explore, research and learn about innovative, step-change solutions and opportunities. The course is cutting-edge – taught by a wide range of experts alongside a diverse cohort of students.

I would 100% recommend this course to others in the industry. Through this course we will begin to transform the industry.

Kate Hall
(CEM 2016) former Design Director HS2 Ltd.

I am not an academic but the academic training I received during the CEM programme has changed the way I approach problems in industry. I can appropriately use the rigours of academic research and testing to make better decisions that get me to the right solutions faster.

Megan Knights
(CEM 2015) Project Manager, AECOM

It feels like I have been walking around with my eyes closed for years and the exposure to all of this knowledge, experience and perspective has opened them wide. It's mind-expanding ... Transformational!

Rob Higginson
(CEM 2018) Commercial Leader, Laing O'Rourke

With a career in design management at Costain spanning over 14 years it was time to plan the next stage in my career. I chose the Cambridge CEM due to its positioning as an advanced leadership programme.

The CEM programme proved to be transformational for my understanding of the subject matter covered and how I thought about delivering change. Near the end of the programme I moved from Head of Design Management to Head of Data Insight for Costain, something I could not have done without the education provided by the CEM programme. I now focus on how data can be used to improve people's lives through delivery of data-driven decision making, something all large companies will need to do to be sustainable businesses in the age of the fourth industrial revolution.

Dan Rennison
(CEM 2016) Head of Data Insight, Costain Ltd

Construction Engineering Master's degree
The leadership programme for the construction industry

Testimonials from industry

> *The only Master's-level course that provides the core understanding of how to influence and advance our industry. This is vital for our future leaders.*

Tim Chapman FICE FIEI FREng
Director at ARUP – Infrastructure

> *Throughout the past 10 years the CEM programme has provided a valuable and stimulating learning environment for some of the future leaders of the construction industry. I have greatly enjoyed the sessions I have had the privilege to present as part of the programme, not least because they have benefitted from lively and challenging questions and feedback from the course participants. I hope the programme continues to go from strength to strength.*

Nick Raynsford
Deputy Chairman of Crossrail; Former Minister for Construction (1997-2001) and Minister for Housing (1999-2001)

> *This course has been a wonderful and innovative introduction for the construction industry. The programme, colloquially termed the 'MBA for the construction industry', is tailored to senior industry leaders, providing them with strategic insights and tools to further develop themselves and positively impact the sector.*

Dr Shaun Fitzgerald FREng
Director, The Royal Institution; Royal Academy of Engineering Visiting Professor, Department of Engineering, University of Cambridge

We are privileged to work with a dedicated group of CEM Fellows who support the CEM core academic team (pages 40-41) and a strong and continually growing list of experts who contribute to the programme. Contributing experts include but are not limited to:

Dr Mark Bew
Chairman, PCSG; former Chairman, BIM Task Group

Professor Dame Carol Black
Expert Adviser on Health and Work to NHSI and PHE; Chair of the British Library

Tim Chapman
Director, Arup

Professor Keith Clarke
Former CEO, Atkins

Steve Gooding
Former Director, RAC Foundation; former Director General, Department for Transport

Professor Peter Hansford
Honorary Professor at UCL; former UK Chief Construction Adviser

Dr Darryl Murphy
Head of Infrastructure Debt, Aviva Investors

Liam O'Keefe
Project Finance Advisor and Consultant; former MD Crédit Agricolé CIB

Nick Raynsford
Deputy Chairman of Crossrail; former Minister for Construction and Minister for Housing

Dr Mark Raiss
Engineering Director, Civil Infrastructure, AECOM

Brigadier Sara Sharkey
Ministry of Defence

Hannah Vickers
Chief Executive, Association for Consultancy and Engineering (ACE)

> *As occupations change and the associated competencies diverge from traditional trade definitions to more multi-skilled and behaviour-led requirements, there is a need to look at how the education system and funding arrangements… are equipped to adjust and support these changes encouraging all standards and qualifications [to] have appropriate future skills content.*

Construction Leadership Council (2019) Future Skills Report

Research and Innovation

Over the last 10 years our research has focused on key issues affecting the industry. Use this section to explore a selection of our research activities and outputs.

Centre research explores solutions to current industry challenges and delivers outcomes designed to drive transformation in a fast-changing digital age.

The following pages outline our core research focus areas, highlighting some of our past, present and planned research projects, through impact case studies, case study extracts and project summaries.

Research is conducted by our core academics, Construction Engineering Master's (CEM) students, PhD students, research associates and a wide network of collaborating individuals and organisations.

Visit our website to view details of all current research projects and to download full impact case studies.

Core research focus areas include:

A research portfolio for industry impact

The Centre has played an important role in bringing investments and strategic research centres to Cambridge through early discussions or input into securing funding, which further strengthen the scope and partnerships of the Centre – including, for example...

62

Research grants* valued at >£15.7 million

98

Completed Master's research dissertations and **20** completed PhD theses

34

Research awards to the Centre

Research Centres together valued at:

£28.6m

- Centre for Digital Built Britain (CDBB)
- Cambridge Centre for Smart Infrastructure & Construction (CSIC)
- Centre for Doctoral Training on Future Infrastructure and Built Environment (FIBE2)

The Centre contributed to a Cambridge consortium awarded

£22.1m

from the government fund 'Advanced Manufacturing Supply Chain Initiative (AMSCI).

*With Centre funding and/or core Centre academics as Principal or Co-Investigators.

Collaborations and partnerships

Since its launch the Centre has been a catalyst for multiple new partnerships, collaborations and research projects that have delivered tangible benefits for all stakeholders and leveraged substantial additional research funds.

Collaboration offers industry access to the brightest minds and opportunity to benefit from evidence-based research. The Centre works closely with industry partners and policy organisations to foster outputs that target specific challenges and offer UK construction companies a competitive edge. We invite partnerships to engender the research, innovation, leadership, and impact that will transform the future of the construction industry.

> *Collaboration and innovation between industry and academia are key to optimising the opportunities of smart infrastructure and the digital revolution. Working together with the Laing O'Rourke Centre for Construction Engineering and Technology on projects such as Staffordshire Bridges combines our expertise and delivers greater impact to infrastructure and construction for the benefit of current and future generations.*
>
> Dr Jennifer Schooling, OBE
> **Director of the Centre for Smart Infrastructure and Construction (CSIC)**

> *The Laing O'Rourke Centre for Construction Engineering and Technology provides a gateway to world-class evidence-based research which is helping to transform construction and educate future leaders who can drive the changes and innovations needed. The Centre has grown from strength to strength over the past 10 years, and I look forward to what can be achieved in the years to come.*
>
> Professor Lord Robert Mair CBE FREng FICE FRS
> **Emeritus Professor of Civil Engineering; Director of Research at the University of Cambridge; Former President of the Institution of Civil Engineers (ICE) 2017–18**

3D Point Cloud of Intersection in London, UK.
Researcher: Dr Bella Nguyen

Collaboration and interdependency

Collaboration is regularly proposed as a mechanism to achieve improved working relationships, information exchange, quality and timing, and to reduce conflicts, risks and costs. Construction Engineering Master's student (2015), Alessandra Villa, Associate at Arup, investigated the enablers for collaboration between designers and contractors in design and build projects in the UK.

Read the full case study on our website.

Industry – academia collaboration

Collaboration between industry and academia can drive innovation.

In this impact case study, Dr Liam Butler, now Assistant Professor of Structural and Materials Engineering at York University in Toronto, explores industry-academia collaboration and innovation in the context of a Staffordshire Area Improvements Programme project which was delivered under budget and ahead of schedule.

At the time of writing, Liam Butler was a Research Associate at the Centre for Smart Infrastructure and Construction (CSIC), supervised by Dr Mohammed Elshafie, Deputy Director of the Laing O'Rourke Centre for Construction Engineering and Technology.

Read the full case study on our website.

Engage with us

Talk to us so that, together, we can discuss how you might get involved in current or future research, or how we can help you solve your problems.

This can include short bespoke consulting projects, seconding an employee within the Engineering Department to undertake a fixed-term research project or longer-term engagements collaborating on PhD projects or as a member of research consortia. Please contact our Centre Manager to start the conversation.

Our website features a full list of our current research projects and interests.

Core research focus area:
Skills

The Construction Leadership Council Future Skills Report (June, 2019) featured research conducted by Construction Engineering Master's students on the topic of skills in the industry. The report presented four examples of skills-based research aimed at helping the industry to anticipate future skills needs.

Digital competence for a digital era: A construction design-sector practitioner perspective (Robson, K. CEM 2018)

This study highlights that digital competence is much broader than operational skills: it encompasses a combination of competence attributes, underpinned by intelligent problem-solving that applies digital solutions and data concepts to fulfil outcome needs. From reviewing a small sample population of design practitioners, the study suggests only one-in-three practitioners achieve an advanced digital proficiency rating, indicating that the UK design community is not yet fully equipped to leverage opportunities presented by a digital transformation. It is suggested that business managers focus efforts on raising practitioner proficiency specifically in problem-solving and data literacy.

BIM in higher education in the UK and future industry requirements (Redman, J. CEM 2018)

Given the rapid adoption of BIM processes and technologies, the industry is facing a skills shortage and research shows that higher-education institutions (HEI) worldwide are reacting slowly to the construction industry's BIM skills requirements. There is little to inform construction industry firms about new graduates' BIM skills and even less describing how firms will need to confront this skills gap to meet industry trends up to 2025. This study involved interviews with industry professionals and academics and a survey of UK HEI course leaders about the future BIM progression and current state of education respectively. It found that undergraduate BIM education focuses on teaching BIM modelling software and is varied with regards to how this is placed in context of industry practice. It concludes that undergraduates are generally not provided with an opportunity to work collaboratively in cross disciplinary teams to prepare them for the workplace. The study recommends that firms focus on collaborative training with their supply chain, focusing on data management and contextualising BIM rather than the modelling technology itself.

The susceptibility of structural engineering to automation and its potential implications for the future of the profession (Patilia, R. CEM 2018)

Considering the era of the Fourth Industrial Revolution, this study assesses the potential for automation in structural engineering. It determined that between 21% and 66% of the tasks within the profession are susceptible to automation, depending on various scenarios of adoption of artificial intelligence and automation technologies. It is suggested that a solution to the rise of automation is to create new multidisciplinary roles to maximise uniquely 'human' characteristics, focusing on higher value, non-routine tasks.

Understanding how 3D vs 2D design information influences skilled operatives' productivity (Corlett, B. CEM 2018)

With the advancement in affordable mobile computing systems, viewing construction information in 3D space on a construction site has been viable for several years. Yet this technology is still broadly overlooked for use by construction operatives. By analysing empirical data collected during a series of field trials, this research determines differences in the performance of fabrication operatives when using 3D vs 2D design information. The findings suggest that 3D design information allowed the most efficient use of working time, the least number of errors and the quickest time to completion. However, the improvements were slight when the whole population was considered without any demographic grouping. Further analysis based on certain participant traits suggested that 3D design information formats could compensate for low spatial cognition and significantly improve younger and less-experienced participant performance.

Electronic copies of the above-cited research may be requested via **cem.admin@construction.cam.ac.uk.**

> *We must constantly challenge the status quo and always keep ahead of the curve. That means our focus reaches beyond the technologies of today to the innovations and disruptors that will shape the future. To achieve this we aim to harness the brightest minds to generate ideas and implement innovation in our industry.*

Professor Campbell Middleton

Director of the Laing O'Rourke Centre for Construction Engineering and Technology

Core research focus area:
Offsite manufacture for construction

Widespread adoption of offsite manufacturing processes and design for manufacture and assembly has the potential to dramatically improve industry outcomes.

Modular housing

The Centre is partnering with the Cambridge Centre for Housing & Planning Research, based in the Department of Land Economy at the University of Cambridge, to identify key research projects with particular focus on increasing the adoption of modular housing solutions.

Small modular nuclear reactors

The Centre Director supervised research by PhD student Clara Lloyd on offsite build for small modular nuclear reactors (SMRs), which was jointly funded by the EPSRC, Arup and the University of Toronto. The project investigated whether modular construction of SMRs was feasible given manufacturing principles, current offsite industry best practice and applicable transport constraints. The research project found modular build of SMRs was feasible for reactors smaller than 450 MWe and concluded modularisation could reduce SMR construction schedules by as much as 50% and total construction costs by up to 25%, relative to current conventionally-built large reactors.

Offsite Construction.
Image courtesy of Laing O'Rourke

Offsite manufacture for construction

A methodology to quantify the benefits of offsite construction

Offsite construction is a key area of research within the Centre due to its strategic importance within the construction industry and the opportunities it creates to improve productivity.

Academia, industry and government collaborate on research to support decision-making

The Centre is the research contractor for a project entitled 'Methodology to quantify the benefits of offsite construction' in collaboration with CIRIA (Construction Industry Research and Information Association), and working with more than 20 industry and government partner organisations. The final report was published in March 2020.[1] This work stems from a desire to drive the implementation of offsite construction in the industry through evidence-based research which supports decision-making on projects.

The government has indicated its support for offsite construction through adopting a "presumption in favour of offsite construction"[2] across five government departments. The benefits of offsite construction are widely declared: the July 2018 report by the House of Lords Science and Technology Committee 'Offsite manufacture for construction: Building for change'[3] sets out opportunities for increasing productivity in the sector, improving the quality and efficiency of buildings and reducing environmental impacts. Currently there is limited objective, evidence-based research to validate the suggested benefits and uptake across the sector remains limited. This collaborative research aims to define a consistent methodology for quantifying project outcomes and assessing the impact offsite construction has on project performance, allowing key stakeholders and policy makers to make evidence-based decisions and recommendations.

1 JANSEN VAN VUUREN, T, MIDDLETON, C (2020) Methodology for quantifying the benefits of offsite construction, C792, CIRIA, London, UK (ISBN: 978-0-86017-897-2) www.ciria.org/c792

2 https://www.gov.uk/government/publications/autumn-budget-2017-documents/autumn-budget-2017

3 https://publications.parliament.uk/pa/ld201719/ldselect/ldsctech/169/169.pdf

Key findings

The research project analysed data from six different organisations and 46 completed school projects with different levels of offsite constructions. Key findings of the research highlight the challenges faced in establishing robust benchmarks for performance of construction projects. The lack of available and consistent data on projects demonstrated the need for a coherent approach to measurement of project performance and outcomes in the construction industry. This applies to projects across the spectrum from traditionally constructed projects to those with high levels of offsite construction. The data and evidence gathered need to be more consistent across the industry to demonstrate the benefits of offsite construction.

Where to from here?

The metrics and methodology described in the report were devised in collaboration with industry and provide a consistent approach for evaluating project performance on completed projects. Adopting this methodology consistently across the industry would start the process of gathering the evidence needed to understand the correlation between construction approach and the benefits that could be expected.

The Centre intends to build on this research project through continuing the process of collecting and analysing project performance data to establish an evidence-base of project performance. Initiatives are underway to continue this research and broaden the application to different sectors, including transport infrastructure. The opportunity to explore interesting issues raised during the research process through a 'deep-dive' engagement with key stakeholders is also being pursued.

Core research focus area:
Digital engineering

Digital engineering

Digital advances are already transforming the way information is used by the supply chain at all stages of the construction process. Smart sensors and data analytics are providing real-time information on operation and performance.

Centre research associates are working with the Centre for Digital Built Britain (CDBB) and industry partners including Bentley, Trimble and Topcon to progress the Digital Engineering research agenda.

Information technology

The Construction Information Technology (CIT) Lab is part of the Centre, and is directed by Dr Ioannis Brilakis. The CIT Lab is a state-of-the-art facility set up to address issues related to infrastructure sensing (from the construction phase and beyond), data analysis and knowledge generation. The CIT's strategic objectives aim to solve complex engineering problems and automate laborious inspection, control and monitoring tasks through decision support tools that recognise data patterns, retrieve useful information and generate knowledge of the built environment.

Smart infrastructure

Tunnelling in close proximity to an existing tunnel is a recurring challenge in densely populated cities with underground transportation networks. Increasing urbanisation may lead to increased use of underground space. Centre PhD student Dr Chang Ye Gue, the Centre's deputy director Dr Mohammed Elshafie and the Centre for Smart Infrastructure and Construction (CSIC) consolidated smart tunnel research by using state-of-the-art sensing technologies on live tunnelling projects in London. This approach used advanced centrifuge modelling to develop a novel analytical tool that provides realistic prediction of the response of existing tunnels to ground movements associated with nearby tunnelling activities.

Fibre optic monitoring

The Centre and CSIC collaborated with the Staffordshire Alliance in the delivery of the Stafford Area Improvement Programme, a £250 million rail upgrade and development project that has been successfully delivered under budget and ahead of schedule. The fibre optic monitoring systems, deployed on two new bridges on this scheme, are capable of measuring changes in strain in real time and have already provided fundamental data useful for determining static and dynamic load response. Network Rail has now funded the installation of two new fibre optic analysers needed for this long-term performance monitoring system.

Digital configurator tools

Dr Jacopo Montali's PhD research focused on creating digital configurator tools to support the early-stage design of prefabricated facades. By capturing relevant design and manufacturing knowledge, the digital application aimed to reduce design time and errors by automating repetitive and standard compliance checks/design tasks. During his PhD, a placement with Laing O'Rourke presented a valuable opportunity to collect data, create a knowledge base and define the tool's applicability to make it ready for use. Jacopo has now founded a start-up company which builds on this work.

Image: Semantically rich as-built BIM models.
Researcher: Dr Manuel Davila.

Impact Case Study Extract

Improving data visualisation in Building Information Modelling

Building Information Modelling (BIM) has been identified as a technology to improve dissemination of information and is integral to digital transformation across the built environment. Marcel Broekmaat proposes a new notation for visualising project information in a BIM context.

Read the full case study on our website.

> *Despite its capabilities related to more efficient dissemination of data in construction projects, Building Information Modelling has not yet been exploited to its full potential. The use of data in context through introduced BIM notations creates an opportunity to empower the next generation of supervisors and engineers.*

Marcel Broekmaat, MSc, MSt (CEM student 2017)
Product Director, Trimble Connect, Trimble Inc.

Asset management related to bridge strikes

Over-height vehicle strikes (OHVS) are a constant and costly problem for asset owners, impacting travel networks and causing traffic delays, damage to bridge structures, bridge closures and injuries. In the worst cases derailments, immediate bridge collapses and fatalities may occur.

In 2017, Centre PhD student Dr Bella Nguyen, now senior research consultant at Arup, tested and deployed an innovative system using video camera monitoring to address both prevention and collision reports – with additional funding from CSIC and London Underground.

The autonomous vision-based system is an affordable solution for asset owners to manage the prevention of bridge and tunnel strikes using state-of-the-art technology.

Read the full case study on our website.

Bella was awarded the John O. Bickel Award at the Construction Research Congress in New Orleans in 2018, with her supervisor Dr Ioannis Brilakis, for her research on bridge strikes.

On receiving the award Bella said:

> *I am extremely honoured to win this award. For me, the important aspect is for the research to gain traction and the award certainly helps to highlight my work... I receive emails from bridge owners on a weekly basis asking whether the system is available for purchase. I hope to explore commercial options as there is a clear need to turn this research into a product for end-users.*

Dr Brilakis said:

> *This is what engineering is about; starting from a real problem that industry brings to us, and finding a clever and simultaneously practical solution that can be deployed widely and effectively.*

> *Our work with the Laing O'Rourke Centre for Construction Engineering and Technology enables industry and academia to come together in pursuit of a shared goal and vision. The synergy between Cambridge research capabilities and Trimble industry knowledge enables exploration of innovative ideas and technologies, especially in areas such as construction, where IT has traditionally been underutilised. Results of such collaboration can be transformative for the building industry.*

Aviad Almagor (CEM student 2017)
Senior Director, Trimble

> *The Laing O'Rourke Centre has demonstrated a long-term ambition and ability to drive transformation in the construction industry. The strong research portfolio focuses on topics identified as critical to this transformation agenda – including the development of digital engineering to enhance productivity, encourage design for value and enable lifetime asset monitoring. The Centre's leading capabilities deliver a world-class Master's course, enhancing the industry's capacity for asset delivery. The impact of the Centre is further strengthened by attracting cross-sector engagement with partners across academia, industry and Government, working together to meet the demands of the next century.*

Dr Mark Bew MBE
Chairman, PCSG; former Chairman, BIM Task Group

Satellite monitoring

Using satellites to monitor structural movements from space

Rapidly-advancing radar satellite imagery technologies can detect sub-centimetre changes on the earth's surface. PhD research by Sakthy Selvakumaran explored whether satellite measurements might transform our ability to monitor infrastructure assets and potentially predict signs of impending failure and collapse.

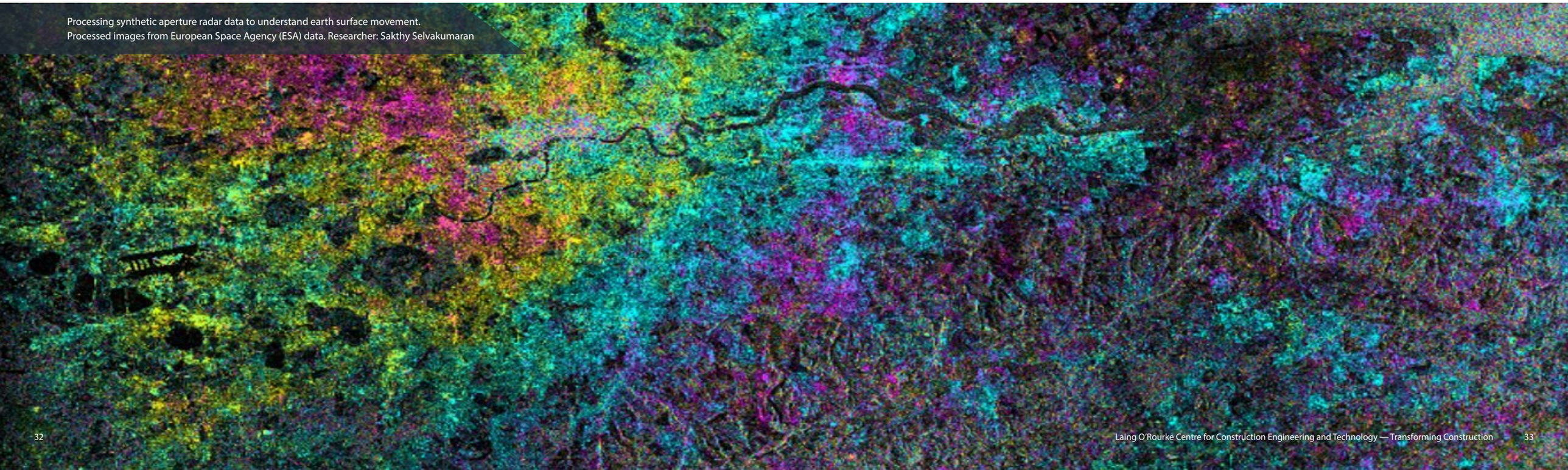
To realise whole-life value of UK assets we need to understand the performance of infrastructure during construction and throughout its operation, particularly as infrastructure is exposed to additional strain from environmental changes. Innovative sensor technologies and other emerging tools can provide new insights to supplement engineering surveying, delivering extra data and valuable information to enable better decision-making for asset management.

The Earth observation sector makes use of a range of sensors, providing access to satellite radar measurements using Interferometric Synthetic Aperture Radar (InSAR) methods. Synthetic Aperture Radar (SAR) uses radar waves which can penetrate cloud, precipitation and even the darkness of night to create digital images at any time of the day or night.

The most common cause of bridge collapse is flooding-induced scour – whereby ground from around structural foundations located in water bodies is removed by the erosive action of water. Scour is of great concern to bridge asset owners, and is currently very difficult to predict since conventional assessment methods involve very resource-demanding monitoring efforts in situ. Sakthy used Tadcaster Bridge, England, as a case study to explore whether InSAR techniques can identify bridges at risk of scour. Tadcaster Bridge suffered a partial collapse due to river scour on the evening of December 29th, 2015 following a period of severe rainfall and flooding. Sakthy analysed satellite images over the bridge from the two-year period prior to the collapse which highlighted a distinct movement in the region of the bridge where the collapse occurred prior to the actual event. This precursor to failure observed in the data over a month before actual collapse suggests the possible use of InSAR as a tool for providing an early warning system in structural health monitoring of bridges at risk of scour.

Her research also studied bridges like Waterloo Bridge and Hammersmith Flyover in central London, comparing satellite measurements with traditional sensors and surveying methods to better understand the accuracy and uncertainty of the data, as well as explore the opportunities and limitations of using InSAR for infrastructure monitoring. She has also been exploring how InSAR can support the monitoring and impact of infrastructure projects such as settlement from tunnelling at Bank Underground station and dewatering and tunnelling activities for Thames Tideway, London's new super sewer.

Sakthy's PhD research was funded by the EPSRC and National Physical Laboratory (NPL), received additional funding from the Laing O'Rourke Centre and technical support and data from the German Aerospace Centre (Deutsches Zentrums für Luft- und Raumfahrt, DLR) and Satellite Applications Catapult. The demonstrated potential of Sakthy's research has attracted significant interest in her post-doctoral plans to carry this research agenda forward. She has been awarded the Isaac Newton Trust/Newnham College Research Fellowship in Engineering, which will be used to establish what will be a growing research group in satellite monitoring of infrastructure within the Laing O'Rourke Centre.



Processing synthetic aperture radar data to understand earth surface movement.
Processed images from European Space Agency (ESA) data. Researcher: Sakthy Selvakumaran

Computer vision – automated progress monitoring using mixed reality

This case study is based upon a Laing O'Rourke Centre for Construction Engineering and Technology PhD dissertation titled, 'Automated Progress Monitoring Using Mixed Reality' by Dr Marianna Kopsida (PhD, 2017).

The challenge to industry

Surveys suggest less than a fifth of construction projects are completed on time, within budget and in accordance with the required quality standards. Progress monitoring is critical to successfully delivering a project on time and within budget but is made difficult due to the complexity and interdependency of activities. Inspection in indoor environments is even more challenging due to the complexity and interconnectivity of tasks, making it one of the biggest challenges faced by a project manager during a construction project.

Despite the importance of project control, the construction industry does not have efficient monitoring systems compared to other industries. Current practices are mainly manual and based on visual inspections, which are error-prone and time-consuming.

Better project control

Efficient methods for monitoring the progress of multiple tasks, especially for indoor environments, are currently lacking. A real-time solution that needs no prior processing and provides a fast, automated comparison between the as-built and as-planned conditions would benefit progress monitoring inspection. Emerging mobile devices can provide both images and 3D information of an environment in real-time. Leveraging this captured real-time data with the design data on-site to compare as-built and as-planned data could provide a real-time automated progress monitoring inspection solution.

Augmented reality in construction

Augmented reality (AR) is a technology which supplements real-world observations by overlaying virtual computer-generated objects. AR offers a means to visualise the progress of a construction project and could facilitate the inspection process by displaying useful information in the inspector's view. Successful AR systems must combine and align real and virtual objects in real environments, in real-time. The challenge for application of AR in construction, particularly for inspection, is in tracking the position of the user and accurately aligning virtual with real data on a mobile device.

Overcoming the challenge

Various methods, both static and mobile, have been proposed for registering the as-planned data to the real data and for tracking the position of the user for augmented reality applications.

Static AR methods have mainly been used for visualising the progress status of a building under construction and processing is performed at the office, not in real-time on-site.

Mobile-based AR methods have also been proposed for facilitating inspection. Methods accurately registering the virtual and the real data have been developed, but they either use heavy and cumbersome equipment requiring a tripod at a fixed location, or use a static camera for capturing photos before augmenting them with Building Information Modelling (BIM) information. These methods lack mobility and reduce the usability of the AR system.

In order to overcome this challenge, mobile marker-less AR systems must be explored. Currently there is a lack of marker-less solutions for inspection and mobile AR inspection systems do not perform any comparison between the planned and the real status of a project under construction to automatically identify progress.

Wearable devices to facilitate inspection

AR allows the user to have useful information in his/her view and interact with it. During an inspection, design and schedule information of the project under construction is needed to perform the inspection. AR systems could overlay the required design information in the inspector's view for the area that is under inspection – saving the inspector time otherwise spent extracting data from 2D drawings. While the inspector moves through the building under construction, the position of the camera can be tracked and the required 3D design information for the area under inspection will be automatically projected in his/her view.

Automated comparison between BIM and real view during the construction of the Dyson Building, University of Cambridge.

Wearable devices leave the inspector's hands free and facilitate movement inside the building. Having the 3D design model registered to the real as-built environment and aligned with the corresponding view of the real environment, the next step is to compare captured as-built data from the mobile device against the as-planned 3D model to detect schedule discrepancies. Colour coding can be used to help inspectors identify objects that have been classified as behind, on, or ahead of schedule from the system.

Microsoft HoloLens tried and tested

Three groups of devices and methods were deployed in this study:

1. 2D images taken from mobile devices and a model-based AR framework
2. Simultaneous Localisation and Mapping (SLAM) methods providing both the estimated position of the camera and a 3D map of the scene in the form of a point cloud
3. RGB-D devices (Microsoft Kinect, Google Project Tango and Microsoft HoloLens) providing direct information about the position of the user and the 3D reconstruction of the as-built environment.

Experiments were conducted with data collected during construction of the Dyson Building at the University of Cambridge Engineering Department. The overall performance metrics of the proposed AR inspection solution using the RGB-D devices were: 76.6% precision, 100.0% recall, and 83.5% accuracy. The 100% recall means all 'built' elements were successfully detected by the developed solution. Some scenes had substantial occlusions due to scaffolding, but the algorithm was still able to detect all 'built' elements.

Microsoft HoloLens performed well on-site. It fitted satisfactorily with a safety helmet and the battery could last for two-hour inspections. Microsoft HoloLens was able to maintain tracking and capture spatial data even during very sunny conditions, despite being an infrared-based technology.

This proposed AR inspection solution enables inspectors to derive instant information about the progress of a building under construction by simply navigating inside the structure. This allows them to identify schedule discrepancies between as-built and as-planned status of a construction project and take timely corrective action.

Read the full case study on our website for details of future prospects and additional improvements to be considered.

Core research focus area:
Productivity

Office for National Statistics (ONS) data suggests that productivity, measured by construction output per worker and per hour, has shown very little improvement in the last 20 years. Many of our research activities, across all topic areas, are motivated by the desire to improve productivity in the construction industry.

The following examples show a selection of research projects approaching this topic from various angles, from digital tools and computer vision to focusing on improving worker wellbeing.

Worker autonomy maintains productivity and improves wellbeing

Improving wellbeing and autonomy provides an opportunity to help construction businesses attract and retain talent leading to improved productivity and growth.

Joanna Vezey, CEM student 2014 and Europe Technical Director at Laing O'Rourke, used her Construction Engineering Master's research dissertation to explore whether increasing an employee's autonomy – allowing a sense of flexibility and control over their working arrangements – has the ability to benefit individual wellbeing while maintaining productivity.

Read the full case study on our website.

Digital approach unlocks productivity

Reinforcement steelfixing, the act of placing and tying reinforcing bars to form a cage before pouring concrete, is a skilled and manually intensive construction activity. It requires a pre-pour inspection by an engineer to check project specifications and reinforcement drawings for the particular pour. James Thorpe proposes a digital approach using two emerging technologies – mixed (augmented) reality and automated as-built modelling – to enable automatic inspection of the cage as it is assembled. This method has the potential to save time, boost productivity and avoid costly rework.

Read the full case study on our website.

> *"Reinforcement steelfixing is a skilled, manually intensive operation, but productivity in this trade today is no better than it was in the 1970s. A digital approach – of in-process visualisation and inspection – unlocks not only faster construction, but a lower skill threshold and greater quality too.*
>
> James Thorpe, MSt (CEM student 2014)
> **Project Engineer, Laing O'Rourke**

Impact Case Study

Vision-based construction worker task productivity monitoring

This case study is based upon a Laing O'Rourke Centre for Construction Engineering and Technology PhD dissertation titled, 'Vision-based construction worker task productivity monitoring' by Dr Eirini Konstantinou (PhD, 2017).

The challenge of improving productivity

Improving productivity in the construction sector is critical to meeting the targets set out in the Government's Industrial Strategy Sector Deal (November 2017) for Construction. Initiatives include targets to be reached by 2025 – a 33% reduction in the cost of construction and the whole-life cost of assets, and a 50% reduction in the time taken from beginning to end of new-build and refurbished assets.

The construction sector has not managed to improve labour productivity for the past five decades. It is estimated that only 50% of total construction time is productive. Current methods of monitoring productivity on site are mainly based on manual observation and work-sampling techniques. These are time-consuming, labour-intensive and error-prone due to the large number of employees and the long-lasting tasks involved on a construction site. These processes are mainly reactive and initiated after a problem has been detected.

Construction requires proactive monitoring of labour productivity in order to detect issues early enough to maintain workflow and avoid costly overruns. Research has brought focus to improving these processes but there is a gap in monitoring the labour productivity of multiple workers at the same time in a way that is accurate, unobtrusive and cost and time efficient.

A new approach to measuring labour productivity

Monitoring of labour productivity relies on the calculation of the labour input and output. All construction entities should be monitored proactively to enable labour productivity to be improved, meaning multiple workers should be monitored at the same time on a daily basis. This offers project managers better information for decision making.

Labour productivity is the fraction of the labour output over the labour input. In construction, the labour input is equal to the time workers spend on construction tasks, while the output quantifies what workers achieved during this time, such as the number of concrete buckets poured, the number of steel cages prepared or the metres of brick walls constructed.

This case study proposes a framework to measure the labour productivity of construction workers through their trajectory data. Video data streamed from cameras with overlapping fields of view provide the input. The first method tracks the location of workers across the jobsite over time and returns their 4D trajectories through space and time – this requires that workers are matched under a unique ID not only across successive frames of a single camera (intra tracking) but also across multiple cameras (inter tracking). Two novel computer vision-based algorithms are developed to perform both the intra and the inter camera tracking.

The second method converts the 4D trajectories of workers into productivity information. These trajectories are clustered into work cycles with an accuracy of 95%, recall of 76% and precision of 76%. Such work cycles depict the actual execution of tasks. The overall proposed framework features an average accuracy of 95% in terms of determining the total time workers spend on construction-related tasks.

Case study continues on the next page >>

Core research focus area:
Productivity

Computer vision-based 2D tracking

This type of tracking matches the same worker across subsequent frames of a single camera (intra camera tracking) and returns his/her 2D trajectories. This tracking method is designed for complex working environments. None of the existing computer vision-based tracking methods has succeeded in tracking multiple targets such as workers who share similar appearance under illumination/scale/posture variations or abrupt movements in the long term. This is mainly because construction jobsites are complex environments due to congestion, background clutter and occlusions. The proposed 2D tracking method outperforms the latest state-of-the-art method that also focuses on tracking of construction workers.

Automated 4D worker tracking

This type of tracking requires matching the same entities across different camera views. Such matching is challenging due to the very similar high-visibility apparel of workers, occlusions and congestion. The proposed matching method addresses these issues by using as input the output of the computer vision-based 2D tracking method. It searches for potential matches in three sequential steps. This searching stops only when a positive match is returned for all workers. The first step searches for the strongest match by correlating 1500ms of workers' past 2D trajectories. If this step fails to return a positive match, then the second step applies geometric restrictions in order to define the area within an image most likely containing a positive match for a worker. If more than one potential match is detected within this geometrically defined area, the proposed matching method activates the third step which correlates workers' colour intensity values. The proposed matching method features a very promising performance of 97% precision, 98% recall and 95% accuracy. After all workers are matched across multiple cameras, their 3D locations over time are calculated through the mid-point triangulation method.

Converting the trajectory data of construction workers into labour input

The trajectory analysis-based method for monitoring the labour productivity of construction workers uses as inputs the outputs of 4D tracking. It detects repetitive patterns in trajectories of workers. These patterns depict work cycles. The total duration of these work cycles is equal to the labour input of every worker on a task level. Labour productivity is calculated by dividing the total labour output over the total input. The trajectory data is clustered into work cycles regardless of the type or the number of tasks the workers perform. These trajectories are four-dimensional (4D) and describe the motion of workers across the jobsite over time.

Applying the framework

The performance of the proposed framework in terms of translating the trajectory data into labour input is evaluated with two data sets. The first (data set steel fixing) captures one worker performing a steel fixing task. The second (data set electrical) consists of two workers who perform an electrical task. Data set steel fixing was recorded at a pre-manufacturing facility (Bison), while data set electrical was collected at a jobsite in Cambridge (James Dyson building). The total durations of data sets steel fixing and electrical are 35 minutes and 51.5 minutes respectively.

Productive work cycles are defined as those when workers actually perform sub-tasks while at 'stop', while unproductive cycles depict workers who are not involved in any construction-related task. Therefore, the time the workers spend outside the working areas is returned as unproductive. This section classifies as abnormal the productive work cycles with durations less than 50% of the duration of the maximum work cycle of a worker.

The benefits

An advantage of the proposed productivity monitoring framework is that it does not require prior knowledge about the type or the number of tasks being completed and can be applied to multiple workers at the same time. Workflow inefficiencies and potential management issues can be identified through the abnormal productive cycles or through the trajectories of workers. This framework monitors the productivity of multiple construction workers unobtrusively, accurately and proactively and delivers potential cost and time savings as workflow can be maintained to avoid costly schedule overruns.

> *This research project proposes a fully automated computer vision-based framework for monitoring the labour input of construction workers in order to bridge the current productivity gap.*

Dr Eirini Konstantinou (2017)
Researcher, Laing O'Rourke Centre for Construction Engineering and Technology

Core research focus area: Procurement

Procure-ment

The procurement process plays a critical role in the construction industry. It sets the project culture and defines the value sought and delivered. It thus has a big role to play in transforming the industry.

Procuring for value

Professor Middleton participated in the Construction Leadership Council (CLC) working party on Procuring for Value. This led to the establishment of a research team at the Centre, with funding from CDBB, working in collaboration with Professor David Mosey, Director of the Centre of Construction Law and Dispute Resolution at King's College London, to focus on producing evidence-based research to support policy in this area.

Impact case study extract

Procurement models – early contractor involvement

Construction Engineering Master's dissertation research by Conor Considine investigated the experience of early contractor involvement (ECI) participants in the UK construction industry. This involved clients, consultants, main contractors and specialist supply chains to identify their motivations and the associated enabling factors affecting willingness to engage with the process on future projects.

Read the full case study on our website.

> *The use of protected dialogue, or multi-contractor early contractor involvement (ECI), is a progressive step for this procurement route, allowing for retention of competition from the client's perspective, yet enabling a mechanism which negates some of the barriers to achieving the enabling factors noted throughout this research.*

Conor Considine, MSt (CEM student 2015)

Project Manager, Expanded Structures, Laing O'Rourke

Collaborative approaches to procurement

The potential benefits of collaborative approaches to procurement are the subject of industry discussion and debate. Construction Engineering Master's student Elliot Mawbey looked at whether empirical evidence supports integrating teams earlier in the process to offer valuable advice and assisting designers to develop efficient buildable solutions.

Read the full case study on our website.

> *An immediate recommendation is to limit the use of single-stage tendering; this form of tendering results in a false sense of cost certainty and an increased likelihood of projects being delivered late and over budget.*

Elliot Mawbey, MSt (CEM student 2015)

Principal Digital Engineer Southern UK Lead, Laing O'Rourke

Awards

Awards

We proudly present a small selection of the research awards and commendations presented to people affiliated to the Centre.

2019	**The American Society of Civil Engineers (ASCE) – J. James R. Croes Medal**	The award-winning paper, 'Structural Performance Monitoring Using a Data-Driven and Dynamic BIM Environment' was authored by a Cambridge team – Dr Juan M. D. Delgado, Dr Liam Butler, and Centre academics Dr Ioannis Brilakis, Dr Mohammed Elshafie and Professor Campbell Middleton. (June 2019)
	ICE Publishing Award	The award for environmental engineering and science went to a paper authored by Centre researcher Sakthy Selvakumaran and Christiana Smyrilli, a researcher in the EPSRC CDT in Future Infrastructure and the Built Environment (FIBE).
	Top 100 Most Influential Women in Engineering	Sakthy has also been recognised as one of the 100 Most Influential Women in Engineering by the Inclusive Boards in partnership with the Financial Times.
2018	**Institute of Engineering and Technology (IET) Innovation Award**	Centre researchers in the Construction Information Technology Lab received this award for the development of a framework that automatically generates the Digital Twins (DTs) of reinforced concrete bridges, then measures and maps visible defects on the DT helping management of repair work. (November 2018)
	WISE Woman in Industry Award	Kate Hall, Construction Engineering Master's student (2016), won this 2018 award, sponsored by Rolls-Royce, in recognition of a woman who has reached a senior role in a STEM career and is an inspiration and role model for women at earlier stages of their careers. (November 2018)
	Innovation Competition in Construction Engineering and Management (ICCEM)	Dr Ruodan Lu and Dr Philipp Hüthwohl won first prize for their 'Automated System for Generating Digital Twins of Existing Reinforced Concrete Bridges' in Beijing – from a pool of 54 teams. (August 2018)
	2018 John O. Bickel Award	Centre PhD student Dr Bella Nguyen and her supervisor Dr Ioannis Brilakis received this award at the Construction Research Congress in New Orleans. (March 2018)
2017 & 2016	**Forbes Magazine Top 30 Under 30**	Centre researcher Sakthy Selvakumaran (Newnham College) was named in the Forbes Magazine Top 30 Under 30 List – Europe, 2016.
	Institution of Engineering and Technology (IET) Awards	Sakthy was also awarded a Postgraduate Scholarship at the IET Awards 2017.
	Fiatech Outstanding Student Research Project prize	Centre PhD student Stefania C. Radopoulou received this award for her work developing road infrastructure sensor systems in vehicles. (May 2016)
2015	**Henry Adams Award – Institution of Structural Engineers**	This award was presented to Professor Campbell Middleton and Dr Andrew Jackson for a paper published in 2013.
	Institution of Civil Engineers (ICE) Russell Crampton Award	Dr Mohammed Elshafie co-authored the paper 'Fibre Optic Monitoring of a Deep Circular Excavation', which received this award for the best paper in the ICE Proceedings – Geotechnical Engineering for 2014.
2014	**International Tunnelling and Underground Space Award –**	Dr Mohamed Elshafie's group, including researcher Dr Chang Ye Gue and the Centre for Smart Infrastructure and Construction, was awarded the 'Ground Investigation and Monitoring Award' for work monitoring the Royal Mail tunnel during the Crossrail tunnelling works.
2013	**Collingwood Prize, The American Society of Civil Engineers (ASCE)**	Dr Ioannis Brilakis and his former students at the Georgia Institute of Technology, Dr Zhenhua Zhu and Dr Stephanie German, were awarded the 2013 prize for their paper titled 'Visual Pattern Recognition Models for Remote Sensing of Civil Infrastructure'.
	Fleming Award for Geotechnical Engineering Excellence	Dr Mohammed Elshafie received this award from the Institution of Civil Engineers, the British Geotechnical Association and Cementation Skanska.

Thought Leadership and Policy

Our research activities are inextricably linked to thought leadership, as they provide the evidence base to inform discussion, policy decisions and industry practice.

The Centre's growing reputation as a hub of activity and expertise for the transformation agenda enables us to facilitate collaboration and knowledge transfer between academia, industry and government to deliver impact.

Our growing online collection of resources and thought pieces include:

- research outputs: published papers and dissertation abstracts
- impact case studies based on Centre research
- discussion papers relevant to current policy topics
- distinguished lecture series

Select examples of thought leadership from the Centre:

Spheres of influence

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Media communication

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Distinguished lectures

Page 47

Thought leadership through the CEM degree

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Academia delivers impact across industry and government

The Centre's core academics have:

Delivered...

73

Invited conference presentations, **76** presentations at Universities or academies and **95** talks to industry

Authored/co-authored...

136

Academic publications, **222** conference papers and **16** books or book chapters

The Centre's core academics are:

Members and editors of...

14

Academic journal editorial boards

Members of...

15

Professional bodies and have contributed to **39** advisory bodies

Spheres of influence

Centre staff and researchers help to shape policy through membership of and contribution to government and industry advisory panels, committees, summits and workshops, including:

- HS2 Design Panel
- Bridge Owners Forum
- Transport Research and Innovation Board (TRIB) Transport Infrastructure Working Group
- National Infrastructure Commission, House of Lords Science and Technology Select Committee report – Offsite manufacture for construction: Building for change
- Highways England 'Developing our vision for 2050 Strategy Workshop'
- Board of International Association for Automation and Robotics in Construction
- G20 Global Café (G20 Summit Brisbane) 2014
- The Resilience Shift Initiative (established by the Lloyd's Register Foundation in partnership with Arup) Technical Advisory Group
- Transportation Research Board, Information Systems and Technology Committee
- International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII)
- National Infrastructure Commission Young Professionals Panel (Sakthy Selvakumaran)

G20 Global Café (G20 Summit Brisbane)

Alongside the G20 Summit in 2014, Brisbane hosted the inaugural Global Café – an international centre of thought leadership. Seventy-five of the world's brightest minds gathered to discuss important issues around improving human life, future cities, powering the economy, unlocking the opportunities of the digital age and exploring the emerging frontiers of tourism. Professor Campbell Middleton was invited to speak at this hugely successful event which **attracted a live audience in City Hall of more than 2000 delegates across two days**, with thousands more watching the live-stream online.

Bridge Owners Forum

Professor Campbell Middleton is Chairman of the Bridge Owners Forum, launched in 2000 to promote collaboration among bridge owners and to identify research needs to assist best practice management of bridge infrastructure. The forum acts as the research advisor and technical subgroup for the UK Bridges Board.

Participating bodies represent bridge-owning organisations responsible for the vast majority of bridges in the UK and Ireland, including:

- Association of Directors of Environment, Economy, Planning and Transport
- Department for Infrastructure (Northern Ireland)
- Department for Transport
- Highways England
- London Underground
- Welsh Government
- Transport Infrastructure Ireland
- Network Rail
- Sustrans
- Transport Scotland
- Transport for London
- ...and many others.

Audience at a Laing O'Rourke Distinguished Lecture organised by the Centre.

Media communication

Media communication

The Centre is called upon to share research and respond to commercial and public interest issues via various channels and across a wide variety of topics.

> *The construction sector is undergoing rapid transformation as a result of the revolution in digital engineering. The university has a wide portfolio of research projects which aim to solve problems in the construction sector.*
>
> Dr Ioannis Brilakis, as featured in **Microsoft News Centre article *'Engineers could soon check the world's biggest bridges from the comfort of their own office'*** [available online]

Professor Campbell Middleton interviewed on BBC Radio

Featured examples:

TV. 2019
Dr Kristen MacAskill appeared in a 10-part Discovery Channel series called *'Disasters Engineered'* to highlight the subject area of resilience – a key research area for the future of infrastructure and society.

News. 2018
Dr Mohamed Elshafie was interviewed by Business Weekly on his work with The Alan Turing Institute, Imperial College London and 3D printing company MX3D to monitor the performance of a 3D printed footbridge in Amsterdam.

TEDx. 2018
Centre researcher Sakthy Selvakumaran presented a TEDx talk on whether satellites can help us predict infrastructure collapses. The video has been viewed more than 21,500 times on YouTube.

News. 2017
Dr Ioannis Brilakis was interviewed for various articles regarding the Construction Information Technology Laboratory's collaborative project with Trimble, including a Microsoft News Centre article entitled *'Engineers could soon check the world's biggest bridges from the comfort of their own office'.*

Radio. 2015
Professor Campbell Middleton appeared on BBC Radio Cambridgeshire to discuss how smart infrastructure technologies safeguard key strategic structures, including Scotland's Forth Road Bridge. He has also featured twice on national radio in Australia.

Distinguished lectures

Lectures

The Centre's series of distinguished lectures provides a forum for leading industry figures to engage an audience of academics, researchers, policy makers and industry professionals on critical issues of the day.

2015
Dr Bernard Charles (CEO, Dassault Systèmes) – *'Experience thinking: the digital revolution in the experience economy'*

2013
Dr Jean Botti (CTO, Airbus) – *'Aerospace and construction: building the future'*

2012
Tristram Carfrae (Group Board Director, Arup) – *'Virtual construction made real'*

2010
Bill Baker (Structural Engineering Partners, SOM) – *'Inspired dreams or wilful excess: the ethical dilemma of iconic structures'*

Visit our website to view recordings of these lectures.

Dr Bernard Charles (CEO, Dassault Systèmes)

Thought leadership through the Construction Engineering Master's degree

In the context of the Construction Engineering Master's (CEM) degree, the term 'thought leadership' is used to capture a core ambition for the programme: that the research conducted by students becomes an authoritative reference, offering insights to help the construction industry improve performance and build infrastructure that is better suited to current and future needs of society.

CEM students are industry professionals who represent a wealth of knowledge and experience from different sectors and company types. The CEM programme brings students into contact with many leading industry, government and academic experts invited to contribute to the programme. This creates a productive and invaluable environment for stakeholders throughout the sector to interact, sharing experiences to catalyse research and discussions with the power to make a real difference to the industry.

Research and dissemination

CEM research dissertations are typically identified through the participants' professional experience, ensuring results remain relevant to the construction sector and applied to real-world problems.

Conference

During their final year, students present their dissertation research at the annual CEM Dissertation Conference. The conference is fast becoming a key event for the industry, showing continued growth year-on-year as an audience of senior practitioners gather for the opportunity to engage with the latest industry-relevant research and leaders of the future.

Publications

We aim to publish and disseminate dissertation research to create impact within and beyond academia. A research associate has been appointed to work with the CEM Director to manage the peer-reviewed publication of research findings to increase research impact and circulation. CEM dissertations have been used to produce a portfolio of case studies demonstrating the impact of evidence-based research for industry.

CEM students bring their rich experience to the Construction Engineering Master's degree and the Centre.

Students across the three current cohorts represent

980 years'

industry experience

Each cohort individually representing **309**, **339** and **332** years' industry experience.

Thought leadership through the Construction Engineering Master's degree

CEM Annual Debate

Our CEM Annual Debate is a highlight and significant component of the programme. It demonstrates the ability of CEM students to work with a range of ideas, challenge the status quo and to think beyond the traditional boundaries of their roles in industry.

The CEM Annual Debate follows debating chamber rules and is held in the historic University of Cambridge Union Debating Chamber. The event offers participants the opportunity to apply their powers of analysis and persuasion to set out a case and win support.

Topics under debate have included: 'Will construction of the future be unrecognisable to today?' and 'Will the national Digital Twin be a pipe dream for a generation?'

Case study teaching

Case studies have considerable value as a teaching method. The CEM is developing a new style of case study specifically tuned to the construction sector. The approach has a systemic focus, reflects multidisciplinarity and is based on research outputs. While the aim for most existing cases studies is for students to arrive at a decision, we propose to shift the emphasis to solving a problem. A case study considering disaster recovery has been piloted and successfully implemented on the programme. While many participants will not have direct experience of disaster recovery, the case study provides a focus for wider issues in the industry in terms of the challenges of managing complex situations.

Thought leadership – expert witness panels

During the final phase of the CEM programme students focus on the future of construction through the lens of policy development, applying skills developed throughout the two-year programme to create greater links between construction engineering and policymaking.

In recent years Dr Julian Huppert, former member of UK Parliament and currently Director of the Intellectual Forum at the University of Cambridge, has introduced students to the process of policy making, the different drivers of policy change, models for public policy and the underpinning political theories explaining belief systems.

During the last two years, the CEM programme has taken the policy and thought leadership focus further, turning a full residential week into a select committee-style exercise. Students gather evidence through presentations and by questioning expert witness panels featuring a wide range of specialists. The student groups produce a briefing paper presenting one headline recommendation for resolving issues associated with the given topic. In 2018 the cohort focused on the topic of UK housing and in 2019 students tackled procurement.

This exercise has been well-received by both invited experts and students.

> *The Construction Engineering Master's attracts the highest calibre of professionals in their field and this was evident in the quality of debate. Both sets of speakers presented very persuasive arguments making it extremely difficult to decide which way to vote.*
>
> Alexandra Bolton
> **Executive Director, Centre for Digital Built Britain**

> *We thoroughly enjoyed participating in this interesting and well-structured expert witness panel session. The lines of questioning were very relevant – resulting in productive panel discussion for the students, as well as value-add for ourselves. Engaging with the questions and others on the panel, we were struck by some of the similarities and differences between the automotive and construction industries and the value in sharing experiences. This opportunity to reflect on our own processes provoked even further internal discussion after the event and we hope this thought leadership exercise continues to engage with other industries in the future.*
>
> Kelly Gardner
> **Senior Programme Purchasing Manager, Jaguar Land Rover**
>
> Marianne Daniels
> **Senior Manager Purchasing & STA – Global Programmes, Jaguar Land Rover**

> *In volunteering for the panel I had three personal objectives, which were to: meet and listen to a group of future construction industry leaders; take the opportunity to further disseminate information concerning public sector initiatives and guidance; and gain experience of being 'on the stand' in a select committee type context. The event in September 2019 fully met all of these objectives and I found the students' questions provided new perspectives and constructive challenge in relation to my specialist areas. It also provided me with an opportunity to give something back having benefitted enormously from the insights of external practitioners when I did my Master's.*
>
> Andrew Butt
> **Commercial and construction professional and UK civil servant**

Our vision for the future

Our vision, mission and guiding principles are clearly defined and will continue to inform our strategy for the future, ensuring actions and outcomes are aligned and effective. We will build upon our established expertise, collaborations and influence to increase impact in industry and policy.

It is time to work together to make change happen.

Strategic focus

The strategic focus of our evidence-based research strongly supports government priorities identified as drivers of industry transformation. Climate change and the need to reduce emissions remain key to our research objectives.

Focus areas include:

- offsite manufacturing/Design for Manufacture and Assembly (DfMA)
- digital engineering
- whole-life performance
- procuring for value
- improving productivity
- unlocking housing supply
- skills required for the fourth industrial revolution
- achieving NetZero Carbon

Research will provide evidence for sector-wide implementation of new tools and technologies, offering UK companies competitive advantage and supporting leadership in digital construction.

Empowering people

The Centre's Construction Engineering Master's (CEM) degree has established a reputation for excellence and is integral to our longer-term vision to support sector change.

Looking ahead we aim to focus on:

- increasing the number of companies represented on the CEM to increase the range of perspectives present on the programme and to distribute the associated benefits across the sector
- designing and delivering more executive education programmes.

Reach and impact

The Centre is emerging as a highly regarded, independent hub for a wide network of stakeholders interested in transforming the industry. We believe this is a timely opportunity to accelerate delivery of our third pillar – thought leadership and shaping policy. As we continue to develop our education and research programmes, we aim to boost the reach and impact of our activities by working closely with industry leaders and organisations, government and politicians to encourage evidence-based decisions that improve the performance of the construction sector.

We aim to increase the scope and intensity of our advisory impact by:

- working to support industry leadership bodies
- boosting our capacity to respond to calls for evidence
- producing resources and 'white papers' targeting key strategic policy areas
- organising events and facilitating interdisciplinary discussion
- utilising the vast experience of CEM cohorts and expert speakers to contribute to industry dialogue
- communicating results of the above, and research outputs, to underpin policy and company decisions.

Engage with us

Collaboration is key to achieving our vision for the future and the Centre is committed to working closely and effectively with business, industry and policy makers to implement positive and sustainable change. We invite you to get in touch so that we can work towards this vision together.

In the first instance we recommend you email our Centre Manager as she will be able to assist you or direct your query where it is best suited.

Centre Manager:
centre.manager@construction.cam.ac.uk
Tel: +44 (0) 1223 332812

Our people

The Centre has a central team of core academics, administrative staff, researchers, students and a growing network of associated experts allied to the Centre and its vision.

A snapshot, at the time of writing, includes:

Core academics

Professor Campbell Middleton | Centre Director

Dr Mohammed Elshafie | Centre Deputy Director and Laing O'Rourke Senior Lecturer

Dr Ioannis Brilakis | Laing O'Rourke Reader

Dr Kristen MacAskill | Construction Engineering Master's Course Director

Administrative staff

Jan Wojtecki
Centre Manager

Alessandra Cirani
Acting Centre Coordinator

Cara Parrett
Communications Manager

Martina Barone
Centre Coordinator and EA to Prof. Campbell Middleton

Adam Cooley
Construction Engineering Master's Programme Coordinator

Tian Wu
Finance Manager

Academic visitors

Paul Westbury
RAEng Visiting Professor of Construction Leadership

Dr Bill Baker
University Honorary Professor of Structural Engineering Design and Visiting Research Fellow

Dr Shaun Fitzgerald
RAEng Visiting Professor in Sustainable Buildings

Our people

Research and Computer Associates


Dr Khalid A. Abdalla


Paul Fidler


Sakthy Selvakumaran


Nicole Badstuber


Dr Didem Gürdür Broo


Vladimir Vilde


Dr Talia Da Silva Burke


Dr Ying Hong


Clara Lloyd


Dr Haiyan (Sally) Xie


Tercia Jansen van Vuuren


Dr Eirini Konstantinou

PhD Students


Evangelia Agapaki


Maciej Trzeciak


Deryk Chan
(FIBE CDT, University of Cambridge)


Mahendrini Ariyachandra


Jamie Webb


Rebecca Ward
(Laing O'Rourke iCASE)


Kasun Kariyawasam


Dan Brackenbury
(FIBE CDT, University of Cambridge)


Juan Canavera-Herrera
(FIBE CDT, University of Cambridge)


Qianchen Sun


Harry Edwards
(FIBE CDT, University of Cambridge)


Simon Ye
(FIBE CDT, University of Cambridge)

Affiliated University of Cambridge academic staff

(Academics who supervise research funded in full or part by the Centre, or who are working in Cambridge in collaboration with Laing O'Rourke, facilitated through the Centre.)


Dr Ruchi Choudhary


Prof. Gary Hunt


Dr John Orr


Prof. John Clarkson


Prof. Duncan McFarlane


Prof. Joan Lasenby

CEM Fellows

(Experts supporting the core CEM academic team)


Dr Brendan Burchell
University of Cambridge


Dr Julian Huppert
University of Cambridge; former MP


Dr Judith Plummer-Braekman
University of Cambridge; former World Bank financial analyst


Prof. Alistair Gibb
Loughborough University


Dr Benn Lawson
Cambridge Judge Business School


Prof. Phil Purnell
University of Leeds


Prof. Paul Goodrum
University of Colorado Boulder


Prof. Eve Mitleton-Kelly
formerly London School of Economics


Prof. Rafael Sacks
Technion – Israel Institute of Technology


Prof. Peter Guthrie
University of Cambridge

Prof. David Mosey
King's College London

Dr Sam Stanier
University of Cambridge

Dr Paul Heffernan
University of Cambridge

Prof. William J. Nuttall
The Open University

Dr Catherine Tilley
King's College London

External academic partners

(External academics and research projects funded through Laing O'Rourke Centre grants)

Prof. David Mosey
King's College London

Dr Krisztina Kelevitz
University of Leeds

Dr Zahra Sadeghi
University of Leeds

Prof. Tim Wright
University of Leeds

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