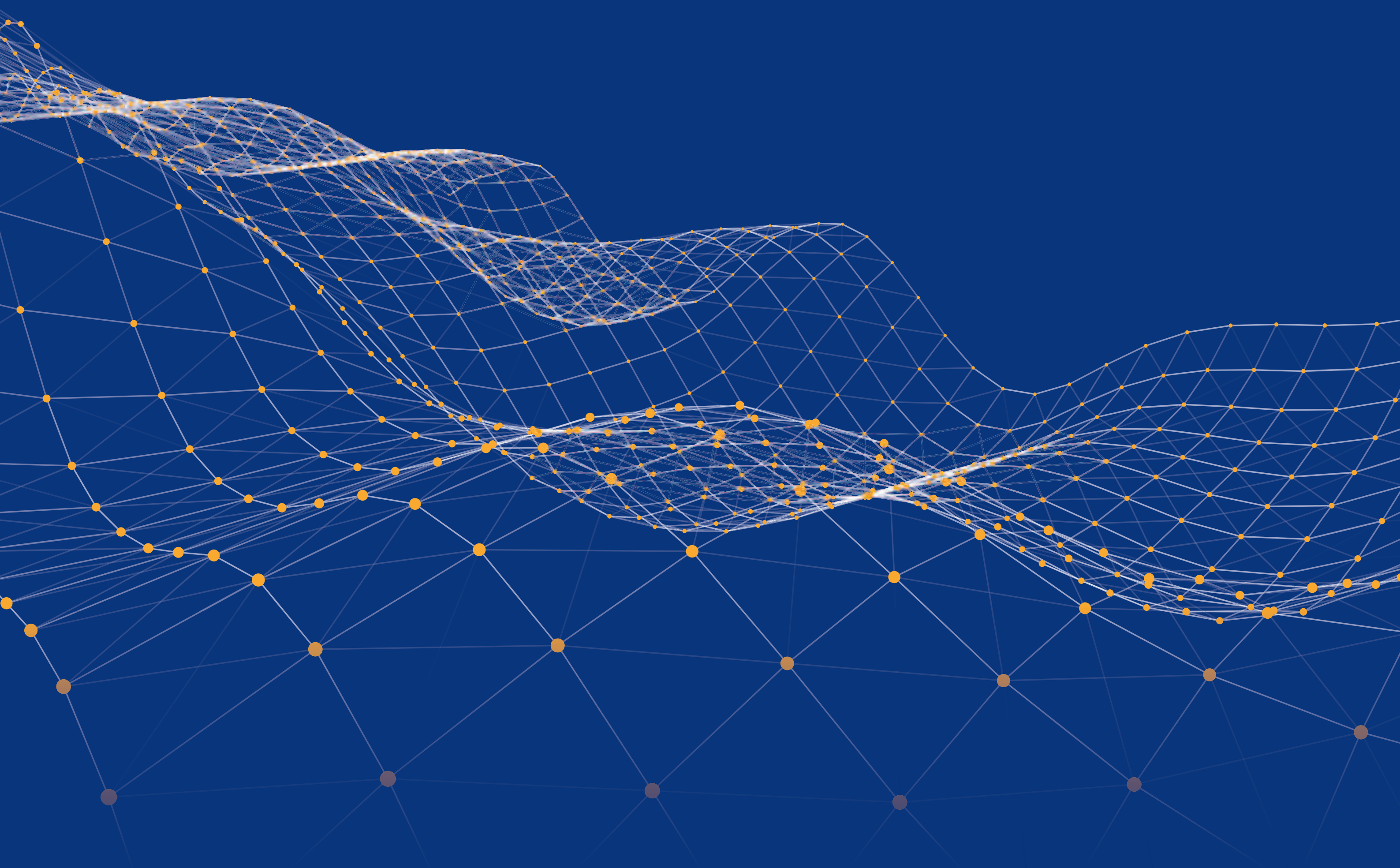
UNIVERSITY OF CAMBRIDGE

10 *Years of transforming infrastructure through smarter information*

Annual Review **2021**



CSIC Cambridge Centre for **Smart Infrastructure & Construction**

CSIC Partners

Infrastructure clients (owners and operators)

Consultants, contractors and asset managers

Technology and information supply chain

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Foreword

Alison Baptiste CBE CEng FICE
Director Project Delivery
Infrastructure and Projects Authority

"This is the decade when we can have the most impact on the 2050 target ensuring infrastructure built now does not require significant net zero retrofit costs nor lock in high carbon in its operation."

This year we have all reflected on what is important and how we live our lives. As we step out of the pandemic with renewed hope and an ambitious government agenda on infrastructure, we must draw on everything we can to achieve net zero carbon in the delivery of that agenda. The changes in our climate present an existential threat and the world's eyes are on the UK as global leaders at COP26 in Glasgow wrestle with the challenge and make decisions for our future.

As the government's centre of expertise for infrastructure and major projects, the Infrastructure and Projects Authority supports the successful delivery of the government's major projects in defence, transport and social infrastructure. Delivering major projects is never easy and to do so whilst meeting the challenges of the Sixth Carbon Budget, with the front-loading of decarbonisation measures it implies, raises the bar still further. We are seeking to make step changes to find smarter solutions for infrastructure construction and operation through data, digitisation, artificial intelligence and modern methods of construction. For instance, one of the think pieces in this publication shows the wealth of data used to forecast electricity demand – a big step on from using the *Radio Times* to predict surges as the nation puts the kettle on in TV schedule breaks!

The Cambridge Centre for Smart Infrastructure and Construction is a leading force in technical innovation and importantly is also driving behaviour change – nudging those of us working in infrastructure to use our influence widely and wisely. This is the decade when we can have the most impact on the 2050 target, ensuring infrastructure built now does not require significant net zero retrofit costs nor lock in high carbon in its operation.

As you read this report, consider what decisions you can influence this week and this year – at work and also in your home, faith, sport and leisure activities. What steps can you make towards net zero? Every step counts.

A decade in numbers

200+ Proof of concept and demonstrators

62 Formal partners

150+ Trade press articles

1500+ Academic publications

30 Awards

£16.8m Other funding

25 Industry secondments

£14.9m IKC funding

3 Spinouts

Introduction by Jennifer Schooling, Director CSIC

Dr Jennifer Schooling OBE
Director of CSIC

This Annual Review marks 10 years of CSIC's journey with industry towards a digital future for infrastructure. As Professors Mair and Soga describe, the journey has been one of close collaboration with our industry partners, working towards data-driven insights for resilient, resource-efficient and cost-effective infrastructure.

Fostering innovation in an industry with low profit margins and high safety requirements has required collective effort, as demonstrated by the projects highlighted in this review, many of which could not have happened without opportunities for working on live construction and infrastructure projects – opportunities which are literally invaluable in demonstrating the viability of proposed solutions in an environment where change can be challenging.

From the beginning, CSIC's mission has been to transform the future of infrastructure through smarter information – learning from the real performance of our built environment assets and infrastructure systems to inform how we design, construct, manage and operate them. The '10 Years of connecting data to better decisions' section in this Annual Review shows how CSIC's projects have developed our understanding of how to use data and digital solutions to deliver on this mission. From understanding the performance of individual assets through instrumentation and monitoring; to informing decisions about their maintenance needs and optimising future design and construction processes; to using information about the assets in a network and their criticality to inform value-based decision frameworks at a system level; to considering the infrastructure needs of our cities; and the role of digital twins in facilitating decision-making. The projects mentioned all required multi-disciplinary collaboration and industry participation for their delivery, hence yielding insights that cannot be achieved through traditional silo-based approaches.

Looking ahead, data-centric approaches to engineering and our built environment remain vital. As Mark Girolami says on page 17, the combination of a data-driven perspective with the fundamental civil engineering knowledge of the underlying physics, chemistry, and basic science that governs operation and performance will yield further insights. This will happen through the cooperation and collaboration of mathematicians and engineers to find and interpret the information 'needle' in the data 'haystack', and together develop the next generation of solutions to the challenges we face.

As Baroness Brown highlights in her article 'Infrastructure, data and the transition to net zero', one of the starkest of these challenges is climate change. We need to build on our progress, and use data as an engineering tool to mitigate climate change. Several of the research projects covered in this Annual Review seek to do this. For example, the ACORN project aims to reduce material use through using innovative robotic formwork to deliver elements that use just enough material and space to perform their structural function and no more. The Inside Concrete project is using strain and temperature data to improve the assessment of concrete integrity and strength, developing approaches to better predict concrete strength based on early age measurements, leading to more efficient utilisation of concrete.

We need to continue to digitalise our industry, and use the resulting data to deliver on the mission of net zero carbon, through better management of our existing assets and more resource efficient design and construction, improving our processes and reducing risk and uncertainty, delivering better outcomes from our built environment.

We very much hope that you will come with us on this important and exciting journey into the future, to develop cutting-edge research and innovative solutions which truly set our industry on the road to managing and delivering a built environment which is zero carbon, resource-efficient and resilient; where people can flourish; and which operates in harmony with the natural environment on which we all depend.

Smarter information: a decade of transforming infrastructure and construction

While CSIC is forward-looking, 2021 invites reflection. Marking 10 years of working with industry and partner organisations to transform infrastructure and construction, CSIC founders Professors Lord Robert Mair and Kenichi Soga recall the beginnings.

Professor Lord Robert Mair CBE
Founding Head of CSIC
University of Cambridge

Professor Kenichi Soga
Chancellor's Professor at the University of California Berkeley

The Centre for Smart Infrastructure and Construction (CSIC) officially started in 2011, but years of research, conversations and collaborations preceded it. Professor Lord Robert Mair, Founding Head of CSIC, and Professor Kenichi Soga, Chancellor's Professor at the University of California, Berkeley, are both world authorities in geotechnical engineering and worked together from the 1990s at the Department of Engineering at the University of Cambridge. Active in the Geotechnical and Environmental Research Group, both recognised that only with data-driven insights could design and construction processes deliver resilient, resource-efficient and cost-effective infrastructure.

The launch of CSIC was timely. A growing digital revolution and period of UK infrastructure construction presented an opportunity for technological innovation in the field.

"The UK infrastructure and construction industry had traditionally been conservative and fragmented, operating within very tight profit margins, with no one organisation having responsibility for the whole life of the asset, which makes developing and adopting innovation challenging. It needed to change," said Professor Mair. "Digital change and emerging technologies brought opportunities to acquire better information on the real performance of assets."

Addressing the challenges of the sector required a multidisciplinary approach. Expertise from many engineering disciplines, including civil, information, electrical, and industrial, as well as additional university departments such as computer science and architecture, all combined to form fresh thinking and integrated solutions from the start.

"We were all cooperative and listened to each other. I think that is the Cambridge spirit," recalls Professor Soga. "There was already some interest in smart infrastructure around the world when we were working with industry partners on a range of projects in the 2000s. We were monitoring structures in the field, trying to innovate with industry by introducing new technologies. We were exploring wireless sensor networks and also distributed fibre optic sensing (DFOS). Our first project using fibre optics was with Skanska and BRE (Building Research Establishment) looking at the possible reuse of piles. We got great data which convinced us of the potential for the technology."

Collaborating with London Underground on a tunnelling project in 2005, the researchers used an innovative fibre optic sensing system to instrument an existing Victorian masonry tunnel running just above a new tunnel being constructed for the Channel Tunnel Rail Link (HS1). This let the project team monitor the existing tunnel during construction of the new HS1 tunnel, avoiding expensive internal support and bracing. The project provided valuable data and highlighted the potential of fibre optic sensing, confirming the value of collaborating with industry in the field to demonstrate the benefits of smart infrastructure solutions.

Confident that this approach could enable step changes by the industry, the Cambridge team submitted a proposal to create an Innovation and Knowledge Centre (IKC) called the Cambridge Centre for Smart Infrastructure and Construction (CSIC) in June 2011. CSIC was one of seven IKCs backed and funded by two government bodies, the Technology Strategy Board (now Innovate UK) and the Engineering and Physical Sciences Research Council (EPSRC).

The goal of the IKCs was to translate research into practice and deliver outputs that industry could adopt. Applying world-class research to the infrastructure and construction sector enabled organisations to develop a competitive, entrepreneurial edge to benefit the UK in the global smart infrastructure market. "Ideas not only came from us but from talking to other people in industry who bring different perspectives," said Professor Soga.

CSIC's principal aim was to be a catalyst for transformation in infrastructure and construction by delivering integrated and innovative solutions to challenges across four areas: sensors and data collection; data analysis and interpretation; whole-life asset management; and cities and infrastructure systems. Monitoring systems combined technologies including fibre optics, computer vision, micro-electromechanical systems (MEMS) and wireless sensor networks to test capabilities and compare results. It built industry confidence through an extensive programme of deployments in real applications, completing 200 proof-of-concepts and site demonstrations and attracting 62 formal partners over 10 years. CSIC worked on many of the largest and most complex civil engineering projects in the UK including Crossrail, National Grid London Power Tunnels, London Underground station upgrades, the Staffordshire Alliance West Coast Mainline railway bridges for Network Rail and HS2.

Working across scales and strategic themes, CSIC has delivered real-world impact. CSIC workshops, training programmes, best practice guides on structural monitoring, industry secondments, academic and industry papers and awards achieved very effective knowledge exchange. Collaborations with technology suppliers enabled the supply chain. Following an initial CSIC demonstration project, industry partner Cementation Skanska developed a complete fibre optic instrumentation solution to monitor piled foundations, embedded retaining walls and other sub surface construction, now branded as CemOptics. There have been CSIC spin-outs, including Utterberry, 8-Power and Epsimon. CSIC always worked with policy makers, regulators and clients to influence decision-making, and to create a market which incentivises industry to adopt whole-life smart and sustainable infrastructure solutions that support the entire life cycle of a system or asset.

"I have always said that CSIC is a 'do-tank' not just a 'think-tank'. Our researchers were always getting up in the middle of the night to instrument tunnels or bridges while they were not in use. They did a great job and always delivered," said Professor Soga. "While CSIC was part of the digital revolution I think it was one of the leading organisations to make it happen – we brought the idea of smart infrastructure to construction."

The ability to be a catalyst for change continues. "I think CSIC always brings the spirit of innovation to industry. Transforming infrastructure and construction is no small task but faced with global challenges of climate change, resource constraint and ageing infrastructure, the need for resilience and adaptability is greater and the value of monitoring and smart infrastructure increasingly visible. CSIC is crucial to this," Professor Soga believes.

The past 10 years has prepared CSIC to provide the tools, technologies and forward thinking to meet the challenges to come. As well as working with other specialist organisations to evolve research expertise, CSIC brings understanding of infrastructure as a complex and interconnected system that must continuously deliver to society.

"Only by learning much more about the real performance of our infrastructure, through sensing and data analytics, can we make step changes in how we design, construct, operate and maintain our built environment," said Professor Mair. "There is an urgent need to exploit digital technologies to establish a smart and sustainable infrastructure industry that enables society to flourish. Only by doing this can we reduce carbon, increase resilience and preserve resources – always the principal objectives of CSIC which, working in close collaboration with industry, still remain highly relevant today."

A decade of impact

2015

The early implementation of the techniques and tools developed within the CSIC programme offers world-beating advantages to major transport programmes, including HS2 and new water, energy, sewerage and construction projects.

Professor Andrew McNaughton
Technical Director HS2 Ltd (2009-2018)

2016

CSIC has been at the heart of this revolution from the start. Innovations arising from its research teams and spin-off start-ups are featured across the Crossrail programme enabled through Innovate18, and others are actively taking forward the sensor and data processing technologies.

John Pelton, MBE Strategic Projects Director
Crossrail Programme Partner Director (now Jacobs, Programme Partner Director East West Rail)

2017

CSIC has enabled us to form small and focused collaborative groups to work on specific problems within our industry, and with its support framework, we have been able to deliver an innovative new product from research stage to full commercialisation (Cemoptics).

Andrew Bell, Chief Engineer
Cementation Skanska

2018

CSIC's leadership in smart infrastructure and the calibre of their work are making significant contributions to better designed, built and managed assets.

David Pocock, Senior Director
Strategic Consulting, Jacobs

2011

£9.5 million from EPSRC and IUK for an IKC

2012

First major event, *Innovation in Construction*, hosted by CSIC, Royal Academy of Engineering and Institution of Civil Engineers (ICE) attracts 170 delegates

2013

- Fleming Prize for the Abbey Mills project
- Inaugural CSIC Distinguished Lecture – Prof Tom O'Rourke
- Spinout – Utterberry

2014

- CSIC Applied Urban Modelling (AUM) Conference
- Smart Tunnel wins at International Tunnelling and Underground Space Awards
- Three industry secondments to CSIC

2015

- 12 award nominations
- Spinout – 8Power
- CSIC wins a total of £5 million from EPSRC and IUK
- 78 Proof of concept and demonstrators from 2011 to 2015

2016

- Spinout – Epsimon
- First International Conference on Smart Infrastructure and Construction (ICSIC 2016) with delegates from 23 countries
- ICE Best Practice Guides published
- *Promoting adoption of Smart Infrastructure solutions in the Transport Sector* published for DfT
- 17 Proof of concept and demonstrator projects

2017

- *Smart Infrastructure: Getting more from Strategic Assets* paper published
- ICE journal *Smart Infrastructure and Construction* launched
- *Intelligent Assets for Tomorrow's Infrastructure* published by ICE
- 19 proof of concept and demonstrator projects
- Eight industry secondments to CSIC
- CSIC starts ongoing collaboration with The Alan Turing Institute

2018

- *Technology and Data in Future Cities* workshop
- 21 proof of concept and demonstrator projects
- *Smart Sustainability* roundtable at the Global Engineering Conference
- CSIC contributes to National Infrastructure Commission's *Data for the Public Good* report
- Focus on public outreach with Cambridge Science Festival and ICE *Tunneling and Engineering Superheroes* exhibitions

2019

- ICSIC 2019 attended by more than 200 delegates
- *Smart Sustainability* paper published
- CSIC moves into new offices at UKCRIC's NRFIS
- 39 proof of concept and demonstrator projects
- Win New Civil Engineer TechFest Rail Visionary Award

2020

- *Flourishing Systems* paper published
- Smart Infrastructure Blog series launched
- 29 proof of concept and demonstrator projects
- 10 industry secondments to CSIC
- CSIC wins two-year follow on funding from EPSRC

2021

- *Carbon Reduction Code* launch
- CSIC hosts UKCRIC *Digital Theme* workshop
- CSIC contributes to CDBB *Our Vision for the Built Environment* report for industry
- Prof Jim Hall delivers the 6th CSIC Distinguished Lecture
- Four industry secondments
- 17 proof of concept and demonstrator projects

2019

The industry-focused and collaborative work of CSIC is transforming approaches to asset management by providing tools for better decision-making. Using data as an engineering tool in this way brings insight and information to improve and add value to whole-life asset management.

Karen Alford, Flood and Coastal Risk Manager
Environment Agency – Asset Data and Information

2020

The collaboration with CSIC on digital twins brings cutting-edge research out of academia and begins to apply it in the real world.

Dan Clarke, Strategy and Partnership Manager
Cambridgeshire County Council

CSIC – 10 years of connecting data to better decisions

The vision of CSIC – collaborating to transform infrastructure and construction through smarter information – is as relevant today as it was at the Centre's launch 10 years ago. In the context of the world's immediate and pressing challenges of carbon zero, resource constraint and resilience, achieving this vision is increasingly time-critical.

Maintaining our existing and new infrastructure is crucial to the continuous delivery of services vital for society and the economy to function and flourish. The need for resilient assets, systems and services that have been and continue to be life-saving has been brought into sharp focus by the life-changing effects of the global pandemic.

Only by better understanding the built and natural environment around us can we improve and preserve it. The work of CSIC has always made the case for understanding the actual performance of infrastructure assets in order to make better decisions for their efficient and sustainable design, construction, operation and maintenance. Information on the condition and capacity of our infrastructure is provided by data, informing resilient and resource-efficient design and supporting low-carbon decisions. Smart infrastructure solutions, informed by good data on real performance, enable benefits to be both immediate – to the asset owners and operators – and far reaching, serving the needs of people, the planet and prosperity.

Over the past decade, as the digital revolution continues unabated, CSIC has worked closely with partner organisations to develop and demonstrate approaches to data acquisition and innovative applications of technologies to help establish the UK market for smart infrastructure and construction. This collaboration is the cornerstone of CSIC's approach and enables application of smart infrastructure solutions to live projects to build sector confidence and accelerate industry uptake for better outcomes.

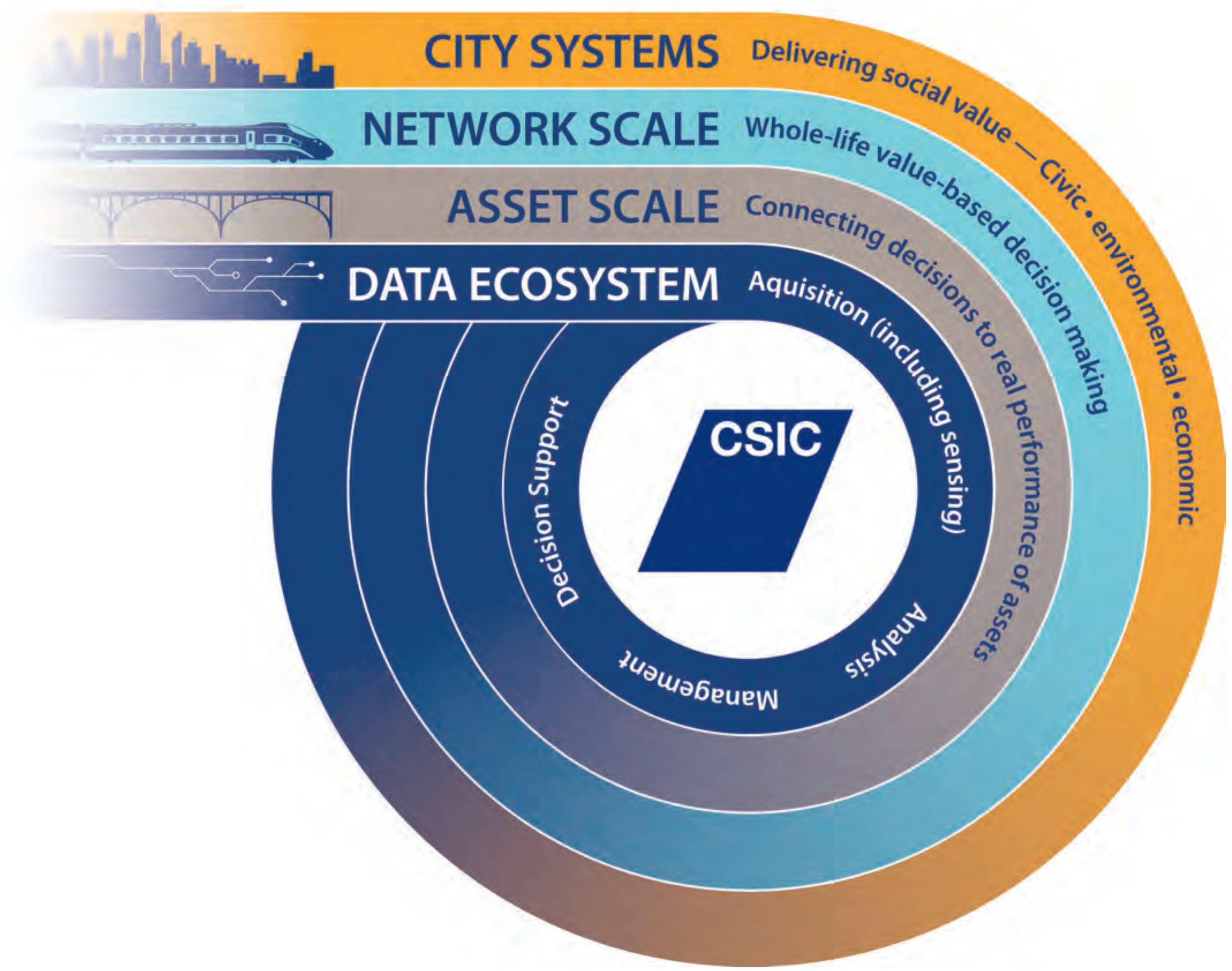
Understanding infrastructure as an increasingly complex and interconnected system of systems, and valuing data as the 'golden thread' of information throughout the entire life cycle of an asset, informs all of CSIC's work. Functioning strategically and at a number of scales across academic research, policy, standards and industry, CSIC has always worked to enable best practice to underpin transformative sector change.

As well as advancing monitoring systems and methodologies to acquire data, CSIC has developed data analysis and visualisation techniques and tools to deliver insights and identify ways of making data a useable and valuable resource. Industry and policy decision-making to address security, efficiency and environmental challenges relies on the support of data as an engineering tool. The mindful and forward-thinking management of data brings opportunity to the infrastructure and construction sector to operate more productively and efficiently – and for the realisation of digital twins and the possibilities beyond.

As the CSIC diagram opposite shows, decision-making throughout the infrastructure and construction ecosystem has data at its core as a valuable asset in itself. The ultimate purpose of delivering value to people and protection to the planet is sustained and connected by data at every level – the asset, the network and the city. The following section of the Annual Review presents a number of projects from the past decade demonstrating how CSIC, in collaboration with partner organisations, has built the case for smart, data-informed, systems-wide decision-making.

Even while celebrating the significant successes of the past decade, CSIC is keenly focused on plans for the next 10 years, collaborating to consolidate progress and continuing to transform infrastructure and construction to meet the opportunities and challenges of the future.

The journey of data – at asset, network and city scales – from acquisition through analysis and management, enabling smarter decisions to deliver a more sustainable, economical and resilient infrastructure system for the people it serves.



Data for better decision-making @ asset scale

CSIC's collaborative work with industry partners is crucial to designing, developing and delivering smart technologies, approaches and tools that address real-life infrastructure challenges. Examples of these collaborative projects are presented below to demonstrate how, over the past decade, our work at the asset scale has provided data to understand the real performance of assets leading to better, safer construction, as well as the advancement of engineering knowledge.

These projects range from early-stage research to develop innovative monitoring techniques, to more recent projects developing cutting-edge data analysis techniques using machine learning, AI and digital twins. This acquisition and interpretation of data at asset scale underpins the case for data-driven smart infrastructure solutions supporting sustainable, whole-life decision-making. Projects below are linked to additional resources for further information.

New insights into pile, retaining wall, and tunnel lining performance

Robust and innovative optical fibre installation techniques were developed for piles, retaining walls **(More)** and tunnel linings **(More)**. These were applied and refined in a series of deployment projects providing important new insights into detailed microstrain soil-structure interaction mechanisms in large, complex civil engineering structures.

Reuse of existing piles

Pile testing with distributed fibre optic sensor (DFOS) systems to monitor the effect of demolition on a high-rise building's pile foundations and surrounding soil. A comprehensive assessment of their suitability for reuse was undertaken. This project with CSIC partner Skanska saved more than £6m, 1000 tonnes of CO_2, and 3-6 months of programme time. **More**

Monitoring of under-reamed piles intercepted during tunnelling using distributed fibre optic sensing

As part of TfL's Bank Station Capacity Upgrade project, fibre optic cables were installed in pre-bored holes in load-bearing piles to monitor the pile performance when intercepted during tunnelling under a multistorey building. This enabled verification of design assumptions to ensure safeguarding of an existing asset. **More**

Self-sensing smart railway bridges

Two types of fibre optic sensor monitoring systems were installed on two new bridges **(More)**. This ongoing collaboration with Network Rail in Staffordshire measures changes in strain in real time and determines the static and dynamic response throughout the whole-life performance of these 'smart' bridges. **More**

Data-centric engineering

Working with data scientists at The Alan Turing Institute on high-level integrated data analytics applied to the vast amounts of continuously collected data from monitoring systems to deliver analytics in real time. This approach uses advanced statistical methods to identify anomalies in data patterns in order to alert asset managers to a change or event in the structure which can be investigated and addressed in real time, while also tracking long-term performance trends.

Digital twins

Monitoring systems that provide continuous and rich data sets are assessed and modelled by structural engineers at Cambridge. Combining structural and data-driven engineering brings new opportunities to smart infrastructure, including the realisation of digital twins. CSIC is creating a demonstrator digital twin of one of the Staffordshire smart railway bridges – a realistic digital representation of the asset 'coupled' via data. Network Rail can use the digital twin to monitor and predict performance by testing or modelling scenarios without interrupting the physical asset or the services it provides. **More**

Assessing and monitoring heritage and ageing assets

CSIC developed a new approach to monitor the response of historic brick vaults to piling-induced settlements using fibre optics, laser scanning and photogrammetry during the London Bridge Redevelopment Project. This approach enabled detection of 3D structural movements with high accuracy and identification of the location and magnitude of cracks, ensuring safe operation of the vaults and the overlying railway tracks during redevelopment construction. **More**

Understanding the response of masonry arch bridges through sensing

CSIC has been working with partner Network Rail to monitor an operational Victorian viaduct in Leeds to assess damage, better understand response to operational loading and to investigate long-term degradation of the structure. Data outputs facilitate decision-making on how to optimally monitor these assets for safe and effective service performance. **More**

Monitoring the response of heritage structures

Working with contractor Dragados, and monitoring arm Geosica, CSIC monitored Grade 1 listed historic buildings St Mary Abchurch and Mansion House during nearby tunnelling for TfL's Bank Station Capacity Upgrade. Combining fibre optics, 3D laser scanning and photogrammetry resulted in an informed observational approach and avoided traditional tunnel mitigation measures, saving in excess of £1m. **More**

Structural assessment and deterioration detection of static highways assets

Working with Highways England and Kier Group to explore the capabilities of acoustic emission (AE) sensing technology for the structural health monitoring of concrete bridges and designing and developing a multi-sensing system comprising AE sensors, fibre optic strain sensors and environmental sensors. Detailed strain and environmental monitoring will help to interpret AE signals and verify the results of damage localisation and characterisation algorithms. **More**

Data for better decision-making @ network scale

This selection of projects demonstrates how CSIC works at the more complex network scale which features groups of assets and requires systems thinking. Through the development of industry frameworks and tools, these assets are categorised and prioritised in order to make decisions about criticality, based on condition, value and risk and how the system operates. Individual assets are understood in relation to the whole group or system, and industry tools enable operators and owners to make better decisions in relation to organisational objectives. Projects below are linked to additional resources for further information.

Value-based infrastructure asset management

A structured methodology to help infrastructure managers develop cost-effective and value-driven asset management plans. A systematic approach identifies needs and requirements from key stakeholders and how these requirements are fulfilled by effective maintenance policies adopted throughout the asset life cycle. **More**

Value-based approach to maintenance prioritisation

Working with maintenance engineers and planners at Cambridge County Council to develop a bridge maintenance prioritisation tool to order annual maintenance activities considering value generated, cost, risks, safety and functionality, heritage status and wider impact on the road network. Incorporating the needs of all stakeholders, the tool enabled the Council to make better-informed decisions and clearly prioritise maintenance activities to ensure maximum value for money spent. **More**

Value-based decision-making maintenance planning tools for metro tunnels

Focusing on a seepage repair strategy for the tunnels, CSIC provided a maintenance policy tool to maximise value provided within budget constraints. This approach incorporated a systematic evaluation of how London Underground tunnels deliver value to the end-user resulting in cost savings, minimised disruption and enhanced value. **More**

Increasing resilience of transportation networks

Development of a robust decision-support framework for terrestrial transportation infrastructure management. Considers diverse types of risks related to natural and man-made extreme events and balancing stakeholders' demands and optimising priorities over asset types. **More**

Asset information futureproofing for whole-life value

A three-stage approach that helps organisations; understand their information retention requirements; identify and assess risks of information losses in the long term; and identify and provide guidance on information futureproofing solutions to mitigate the risks of information loss. **More**

Optimising condition-based maintenance policies for assets with complex deterioration processes

At the bridge level, the scheduling of maintenance activities is optimised for the system based on current predictions for both risk and cost. The goal is to reduce the traffic management cost by combining maintenance activities for multiple bridges across the network. The approach was trialled on bridges with Hertfordshire County Council and demonstrated a 10 per cent cost saving compared to other standard approaches. **More**

Bridges Asset Management Toolkit

The condition-based maintenance approach was used to develop an industry-ready tool for any type of bridge as part of a secondment with Mott MacDonald. The tool has been designed to support asset management planning and business case development for asset owners. It also provides an interface between the DfT Structures Asset Management Toolkit and asset management systems to allow asset data input to be automated. **More**

Data-driven asset management – a framework for linking ISO and BIM standards for whole-life value

Developing through-life asset information requirements and guidance on how to organise and manage data to support asset management. Linking PAS 1192 (BIM Level 2) standards with ISO 55000 (asset management) standards, the framework validates the information model against the asset owners' organisational requirements and objectives. **More**

Risk-informed monitoring and management of critical infrastructure

Taking a data-driven and value-based approach, this project considers a holistic view of management beyond the physical bridge infrastructure. It feeds into developing a business case for risk-informed monitoring and management strategies while considering a whole-life perspective to facilitate a rational, balanced approach to evaluating the effect of hazards, including climate change, on systems, possible failure modes, and associated consequences. A tool is being developed which is intended for industry use. **More**

West Cambridge Digital Twin

Investigating the role of the digital twin (DT) in optimising asset value, this project demonstrates the impact of the DT on facilities management, wider productivity and well-being of the building occupants. Starting with a DT of the Institute for Manufacturing and the West Cambridge campus, the project explores the impact on estate and facilities management to make better operational, maintenance, investment and planning decisions to create value, increase resilience and secure sustainability. **More**

Line of Sight Asset Management Methodology to Support Organisational Objectives industry paper and tool

A methodology and tool that provides a direct line of sight (golden thread) from organisational objectives to asset performance. This enables better-informed decision-making processes for operational, financial, social and environmental outcomes, while providing the foundation for the realisation of digital twins to support whole-life asset management. **More**

BIM maturity assessment tool (BMAT)

This tool supports an organisation's implementation of BIM and provides measurement of the organisation's BIM development maturity, and measurement of the supporting processes. The BMAT was developed to be industry-ready through a CSIC secondment project with Mott MacDonald. **More**

Data for better decision-making @ city scale

Cities are complex entities comprising systems of systems. The following selection of projects demonstrates this complexity and shows how the various systems in a city are linked and interconnected through data. CSIC research bringing focus to the need for responsible digitalisation in cities, with appropriate governance of technology, is positioned centre stage, along with the opportunities that city-scale digital twins bring for viewing and better understanding the interactions of the many systems and services within the city.

Feeding into these are a number of projects from the past 10 years in transport modelling and planning, transport-led urban development, urban farming, district level energy provision and planning for the subsurface. Projects are linked to additional resources for further information.

Transport modelling and planning

London Bridge crowd-sensing and crowd-sourcing

Part of a wide project, open social media data and urban sensors were used to test multiple pedestrian flow monitoring techniques for preventing undesirable crowding conditions to establish patterns of pedestrian distribution for providing effective services in and around the station. **More**

Harvesting spatially and temporally dynamic data on travellers

Investigating the use of GPS-informed journey information and real-time public transportation feeds for scenario testing for potential infrastructure or policy changes. **More**

Adaptive zoning: quantifying costs and benefits of major transport investments.

Economic interpretation of the adaptive zoning method for appraising business cases of major transport infrastructure investment projects. **More**

Understanding travel behaviour in the age of Big Data

Deploying machine learning techniques to infer causal relationships between network conditions and passenger transport decisions. **More**

Responsible and sustainable digitalisation in cities

DC² Digital Cities for Change: next-generation tools for city planning and management

Addressing the disciplinary gulf which currently exists between city managers, engineers and urban designers, this project establishes a significant ongoing research programme to address gaps and identify the digital tools required to deliver a smart city which benefits the citizens it serves. **More**

Cambridge City-Scale Digital Twin pilot: for cross-disciplinary policy decision-making

A prototype model using existing data sources to demonstrate the value of a digital twin for facilitating cross-disciplinary collaboration in policy decision-making. **More**

Forward thinking for future smart infrastructure

Using data and digital twins as an engineering tool for sustainable and smart infrastructure systems. See also p24 of this review. **More**

Urban farming

Growing Underground

Temperature, humidity and CO_2 levels have been monitored at an underground urban farm to develop and validate a Greenhouse Energy Simulation model for the prediction of the energy consumption of the site **(More)** and develop a digital twin of the urban farm to integrate forecasting models, suggest operational changes, and then feed back on the outcome. **More**

District level energy provision

Multi dimensional simulation of underground spaces coupled with geoenergy systems

Model simulations to demonstrate the impact of retrofitting a London Underground line with geothermal boreholes to decrease temperatures in the subway tunnels. **More**

Decarbonising domestic heating

CSIC researchers are working in collaboration with The Alan Turing Institute to take a data-driven approach to optimise the use of data to support more effective urban energy policy and better decision-making. **More**

Saving energy: ground source heat pump (GSHP) applications at city scale

Development of a GIS-based city scale simulation model to estimate how many GSHPs could be installed without losing control of thermal capacity. **More**

Transport-led urban development

The transformation of a historic urban quarter

Learning from good practice across three case studies in integrating urban infrastructure surrounding main urban rail and underground stations, including London King's Cross, to inform BSI smart city standards and strategies for redevelopment and regeneration around rail stations. **More**

City scale: the impact of infrastructure on urban development and redevelopment: evidence from London's history

New ways of examining historic data to uncover and quantify the evolution of urban land use, transport investment and regulatory measures to provide the evidence to calibrate robust forecasting models for new infrastructure and development plans. **More**

Land-use modelling and urban planning

Cambridge Futures

A 'virtual lab' enabling data-led decision-making for economic growth and development, the three-year 'Cambridge Futures 3' modelling study is designing and examining alternative scenarios of workplaces, housing and transport to 2031 and 2051 **(More)**. The modelling work was recently expanded to the national scale to develop the first quantifications for levelling-up and rebalancing of the regional economies in the UK. **More**

Grow Green

Creating climate and water resilient, healthy and liveable cities by investing in nature-based solutions. **More**

Planning for the subsurface

Translucent City

Engineering a translucent city to radically transform the usage of the underground space, this cross-disciplinary study integrates the subterranean part of a city with the above ground 'visible' part. Precursor to Modelling and Monitoring Urban Underground Climate Change. **More**

Modelling and Monitoring Urban Underground Climate Change

Understanding the impacts of urban underground infrastructure, such as basements and tunnels, on shallow subsurface temperature increase at city-scale. **More**

Professor Mark Girolami, Sir Kirby Laing Professor of Civil Engineering and Royal Academy of Engineering Research Chair at the University of Cambridge, Academic Lead for CSIC, and Director of the Data-centric Engineering Programme at The Alan Turing Institute, considers future opportunities that CSIC's continued collaboration with industry partners across engineering sectors, sciences and disciplines will bring.

10 Years of CSIC – Abbey Mills Shaft F, in Stratford, East London, was part of the Thames Water Lee Tunnel Project and is one of the largest, deepest shafts ever constructed in London. Picture courtesy of Thames Water.

CSIC deployed fibre optic strain sensors to monitor deformation in the retaining walls and adjacent ground during excavation. This saved an estimated £10m in risk mitigation for future Thames Water construction projects and won the 2013 Fleming Award.

Making the future: transforming data into insights to deliver value

The founders of CSIC recognised that only with data-driven insights could design and construction processes deliver resilient, resource-efficient and cost-effective infrastructure. In other engineering sectors that previously recognised the necessity to adopt a data-driven perspective, new market opportunities and new business models have emerged such as for Rolls-Royce in aerospace.

The data-driven management of engines enabled Rolls-Royce, as far back as 1962, to launch the 'Power-by-the-Hour' business model where a replacement engine and parts service was provided at a fixed cost per flying hour to the operator. Today, this service now includes Engine Health Monitoring and other monitoring systems, where for example, on-wing performance is assessed using onboard sensors and a global network of maintenance centres are coordinated to minimise downtime. In a similar manner, CSIC has, over the last decade, been pivotal in the comprehensive instrumentation of assets from rail bridges to highways, all now producing data-driven insights into their operating condition. For example, in collaboration with Network Rail, CSIC will soon deliver the first remotely monitored railway bridge on the UK network providing efficiencies in both operation and maintenance. This is a proof of concept that points to a possible transformation in the management of critical infrastructure which would provide safer, more responsive and efficient operation for asset owners and a more resilient service to customers.

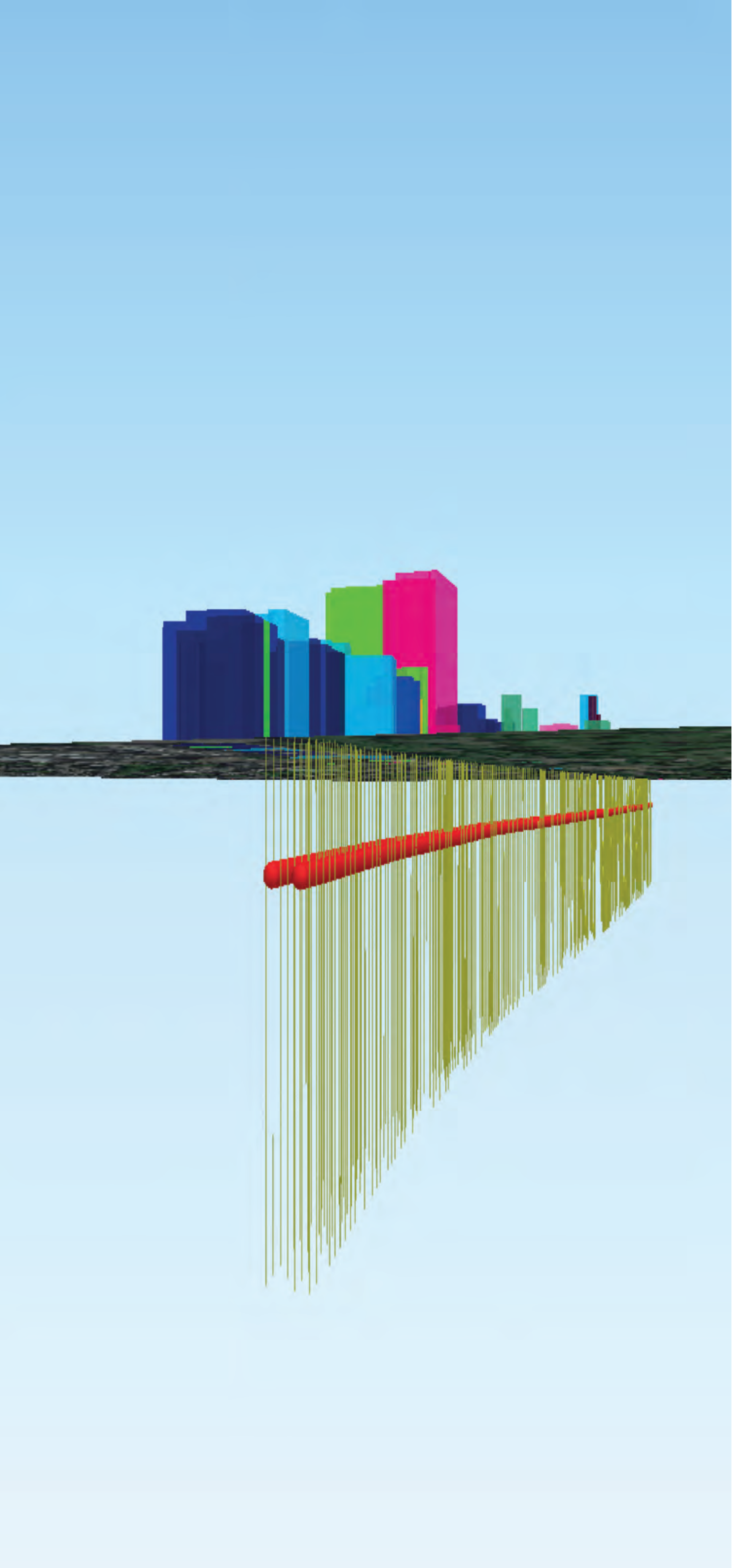
Next consider data and how it can be transformed into information and, ultimately, actionable insight. Sir Ronald Fisher, arguably the father of modern-day data science, in paraphrase said that 'to call in the data analyst after the measurements have been made is like calling for the doctor when the patient has died'. The excitement of the realisation that ubiquitous digital technology was enabling data in its various forms to be gathered at rates and volumes never before imagined gave rise to the Big Data banner. However, as Fisher warned, it is not Big Data that is of value – it is information and insight. It is not enough to just measure. The research area of Data Science is essential for CSIC to develop the new theory, methods and analytic tools which will provide the data-driven actionable insights to meet the scientific and societal challenges our critical infrastructure faces. It will be the enabler for us to transform data into insight, action, control and policy.

The 'Power-by-the-Hour' model originally dealt with the management of single assets given the data obtained from each aircraft. However, operators manage fleets of aircraft for which safety and profitability are complex functions of performance of the fleet as a whole. The same applies to our infrastructure, for example Network Rail is reliant upon its 'fleet' or 'population' of tunnels and bridges to deliver the essential transportation system across the UK. The impact of one bridge being closed cascades across the whole network in a complex, nonlinear manner. Taking a population-based approach by sharing data across assets is one of the next steps in considering the improvement of resilience of our infrastructure. There are deep theoretical challenges to understanding these networks of influence, and how data can be shared to ensure an increase in information (and not an increase in noise). CSIC is instrumental in leading and driving forward this important strand of research and development.

Underlying the design, construction, and operation of many forms of infrastructure is knowledge of the underlying physics, chemistry, and basic science that governs operation and performance. The dynamics of an asset – bridge aerodynamics, energy efficiency of buildings, material properties, structural characteristics, the list goes on – are described by mathematical principles which are well understood in some cases and poorly understood in others. It is essential that we do not lose sight of or neglect the knowledge embodied in the fundamental laws distilled by our predecessors in civil engineering.

The synthesis of both mathematical models describing an asset and informative data from the asset itself is a hugely powerful combination for control and design, with data 'infilling' in cases where the underlying science is not well understood, and the science 'infilling' where data is sparse – examples are constitutive material models, or turbulent fluid flow. This synthesis of data and models has given rise to the popular moniker of the digital twin. There is much foundational research required to deliver safe and efficient digital twins and this is the case across all sectors of engineering. The power to twin at a single asset level, or indeed using physical or socio-economic theories, models and data measured at the population, urban and city scale, provides great promise.

As CSIC looks to the next 10 years, we will continue to seek inspiration, challenges and insight by collaborating across the various engineering sectors and their associated sciences and disciplines. CSIC will remain at the vanguard of synthesising models and data which will ultimately deliver value to infrastructure construction and operation and support better and sustainable services on which society depends.



Making the case for integrating infrastructure with big data, physical modelling and artificial intelligence, Baroness Brown of Cambridge, Julia King DBE FREng FRS, Chair of the Climate Change Committee Adaptation Committee, non-executive Director of the Offshore Renewable Energy Catapult and Chair of the Carbon Trust, calls for digital technology to underpin the transition to net zero.

10 Years of CSIC – schematic of the London Underground Central Line (Westbound and Eastbound) in the City of Westminster coupled with a 3D model of geothermal boreholes.

CSIC proposed boreholes close to Underground tunnels to address overheating problems in the old, deep metro system. The boreholes extract heat from soil near the tunnels, cooling them and their platforms while meeting a portion of adjacent buildings' heating and cooling demands. Schematic by former CSIC PhD student Adnan Mortada.

Infrastructure, data and the transition to net zero

We are going to need to invest in new, low carbon infrastructure to achieve net zero, in particular in our energy systems. The Climate Change Committee's core pathway for the Sixth Carbon Budget in 2035 and net zero in 2050 sees electricity demand more than double; other projections suggest we could increase demand to three times that of today. The Government has announced a target of 40GW of offshore wind by 2030, and this could rise to around 100GW by mid-century. Masked by this huge growth in electricity use we anticipate a dramatic improvement in our energy efficiency; total energy use across gas, oil and electricity is almost 2000TWh today, by 2050 this is predicted to fall to 1000TWh. However, the contribution of electricity is expected to rise from approximately 15 per cent today to 70 per cent by 2050, with renewable generation increasing from 30 per cent to around 80 per cent.

Embedded in the net zero transition of just this one sector by 2050 are a number of challenges:

- How do we minimise the embedded carbon in the infrastructure we build?
- How do we ensure we build the minimum amount of new infrastructure to meet demand to minimise cost and environmental impact?
- How do we optimise operation and maintenance of that infrastructure to provide security of supply and low cost to consumers?
- How do we manage demand and supply in an increasingly complex energy system with local generation at people's homes combined with a grid powered by variable renewables?
- When electricity is our dominant source of power for light, heat, communications, industry, water supply, and transport, how do we ensure the system is resilient to shocks, for example those that the changing climate will deliver?

Key to answering all of these will be how quickly and effectively we learn to integrate infrastructure with big data, physical modelling and artificial intelligence. We need to drive this change – and digital technology can help us achieve a significant proportion of the emissions reductions we need to make by 2030[1].

The standardisation and digitisation of carbon footprinting linked to traceability of materials integrated into digital twins – virtual representations of physical assets – of our structures and equipment will enable minimisation of embedded carbon in design whilst maximising recycling and reuse. These digital twins will store condition and operational data from arrays of embedded sensors. For example, in the case of wind turbines, that condition data will be combined with current weather information and predictions of future conditions to optimise operations, and repair and maintenance schedules for each individual turbine.

The data from the grid about current and predicted energy demand (and of course electricity price) will enable the wind farm operator to decide whether to store electricity, produce hydrogen, sell electricity into the grid or carry out maintenance. The grid operator will be using data and projections about weather, household generation and behaviour, industrial output, travel and transport, generation, storage and other assets to determine electricity prices and the services required to ensure a stable electricity supply.

Digital technology will underpin the net zero transition. Joining up the whole system through sensing, data collection, predictions from physical modelling and application of artificial intelligence to big data sets – for example linking climate and weather predictions, behaviour and decisions in individual households and businesses, and the condition of individual assets is what will enable us to deliver a cost effective, sustainable and resilient net zero transition in the energy system, and across every sector.

The decisions we take today about how we embrace and embed digital technology in our new infrastructure, especially as we 'build back better' from the COVID crisis, will determine the cost and the ease with which we can achieve net zero. The collaborative work of CSIC recognises this urgency – and the value of smart infrastructure solutions and data-driven insights to enable zero-carbon and zero-waste decision-making.

Government, industry, and universities need to be working closely together to realise the potential of digital innovation, delivering education and training across society from infant schools to government officials, to pensioners and researchers, developing new business models, new data infrastructures, and trusted and trustworthy digital systems. A data-led net zero transition has a lot to offer – we have a lot to do to make it happen.

[1] Digital Technology and the Planet, The Royal Society, December 2020

CSIC has developed a body of research throughout the past decade that has built the case for smart infrastructure solutions to add value to industry and address increasingly urgent challenges, including mitigating the effects of climate change, resilience and resource constraint.

10 Years of CSIC – an instrumented continuous flight auger (CFA) pile cage being inserted into the pile bore to monitor reinforced concrete pile performance. After a decade of field trials, CSIC was able to quickly and easily install distributed fibre optic sensor systems (DFOS) to measure, with a single instrumentation system, concrete curing temperature as well as strain during pile testing and a pile's operational phase. DFOS monitoring is now specified in the 3rd edition of the 'ICE Specification for piling and embedded retaining walls (SPERW)' which CSIC contributed to.

Research

The Centre's interdisciplinary approach acknowledges the complex and interconnected system that is our infrastructure, and the CSIC model of collaborating closely with industry enables tools and technologies to be tested on live projects, building confidence and accelerating the commercial timeframe for these innovations.

The following selection of research projects – from exploring opportunities of computer vision in civil engineering and developing tools and techniques needed for future connected, intelligent and data-driven infrastructure systems, to enhancing understanding and more efficient utilisation of concrete and establishing the as-built quality of foundation piles – demonstrates how CSIC works dynamically to transform infrastructure and construction with smarter solutions.

Research project 1
Construction's ongoing journey to net zero

Research project 2
Forward thinking: Using data and digital twins as an engineering tool for sustainable and smart infrastructure systems

Research project 3
Computer vision beyond black boxes – all eyes on infrastructure and construction

Research project 4
Inside concrete

Research project 5
New interpretation framework technique for detecting anomalies in piles from Thermal Integrity Profiling (TIP) data

Research project 6
Closing the loop: Back analysis of sprayed concrete tunnel junctions

Construction's ongoing journey to net zero

Key benefits
- Identifying opportunities for material efficiency in construction

Automating Concrete Construction (ACORN) is a collaborative research project between the University of Cambridge, University of Bath and University of Dundee, and includes a number of CSIC investigators and researchers. The project aims to improve whole-life construction sector sustainability and productivity by creating a culture that takes a fresh, holistic approach to the manufacture, assembly, reuse, and deconstruction of concrete buildings, leading to a healthier, safer, built environment. ACORN, which began in early 2019, continues through 2021 and aims to deliver a prototype structure that will act as a full-scale demonstrator for the research.

Categorising material efficiency in construction

ACORN researchers have identified a clear need for impactful and cost-effective actions to reduce overdesign and improve material efficiency if the construction industry is to achieve net zero carbon targets by 2050.

Until recently, much of the research and innovation on sustainable construction has brought focus to the operational emissions associated with a building, particularly on improving thermal performance. However, there is increasing recognition that capital emissions, those emitted during the manufacture of construction materials and those embodied in the materials themselves, are of similar importance.

Buildings and construction are responsible for 40 per cent of global energy-related CO_2 emissions, and cement production is a significant contributor. Recent reports [1,2,3,4] make various suggestions of how to reduce carbon, including policy and public procurement changes, carbon capture and storage, alternatives to Portland cement and demand side measures.

The ACORN team has categorised opportunities for material efficiency by stage of construction as shown in Figure 1 and expanded on below:
- Structural form: including the choice of grid size and using lengths of span greater than required
- Overdesign: plans specify more material than required for structural purpose, for example prismatic beams
- Over-specification of structure: designed for loads greater than experienced
- Over-specification of materials: materials chosen with greater strength than required
- Over-ordering: to avoid running out
- Over-delivery: excess quantity or specification than ordered, for example concrete that is stronger than needed
- Onsite waste: unused materials
- Over-binding: concrete with same strength performance but excess binder index
- Excess clinker (solid material produced in manufacture of cement): concrete with same binder index, but a greater proportion of clinker than required
- Efficiency of clinker plant: clinker produced at a plant without the best available technology
- Efficiency of clinker production: clinker produced while plant is operating below best observed performance
- End of life recovery: emissions resulting from (or mitigated by) treatment of waste at end of life.

The potential for improvement varies, depending on material source, construction stage and process. According to estimates[5] one of the biggest opportunities is in the overdesign category, where waste can be as high as 50 per cent. Beams are often stronger than needed, and design can be led by labour costs rather than minimum material consumption. The ACORN project seeks to address this significant material reduction, and therefore carbon reduction, opportunity by using material only where needed to support the load.

In total, the potential percentage reduction for all categories could be more than 90 per cent, if inefficiencies from every stage of design to construction are eliminated. Further research is needed to confirm these estimates and develop methods to achieve them. The ACORN team will be collaborating with a number of other research groups over the next 18 months to investigate other types of construction project and quantify the losses more precisely. These include investigations into decarbonising precast concrete in conjunction with the Centre for Industrial Sustainability, decarbonising infrastructure projects as part of a collaboration with Expedition Engineering, and improving material flow data gathering in construction in conjunction with Costain.

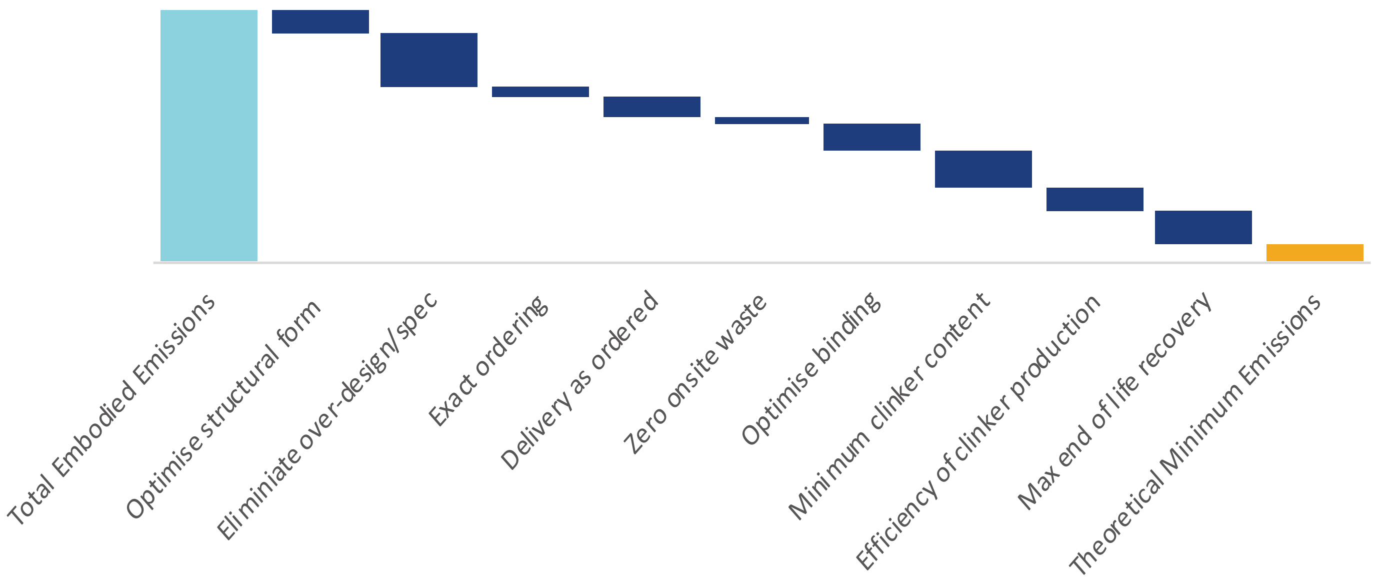


Figure 1. Opportunities for material efficiency by stage of construction. (This figure has been scaled to account for non-mutually-exclusive savings: the value of each area would vary depending on what order in which the areas were tackled.)

Contact CSIC Investigator Dr John Orr
Team Dr John Orr; Professor Tim Ibell (Univesity of Bath); Dr Paul Shepherd (University of Bath); Dr Ajith Parlikad; Dr Saverio Spadea (University of Dundee); Dr Robin Oval; Dr Daniel Summerbell, Mrs Diana Thomas-McEwen

For more information about the ACORN collaboration see the website automated.construction

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Forward thinking: Using data and digital twins as an engineering tool for sustainable and smart infrastructure systems

Key benefits

- Systems of systems thinking to understand and anticipate future infrastructure systems and enable sustainable and resilient digitally-enabled decision-making

Considering change and consequences

CSIC is active in developing the tools and techniques needed for the planning and design of future smart infrastructure systems. These systems will be connected, intelligent and data driven. The past, present and future work of CSIC enables this transformation of infrastructure and construction by collaborating with industry to find ways to turn data into information – providing insights for informed, efficient, climate-conscious decision-making.

This collaborative and multi-disciplinary research project supports better understanding of the big and complex picture when planning and designing future smart infrastructure systems within our built and natural environment. It not only focuses on the opportunities that data and artificial intelligence bring, but also highlights the importance of understanding and implementing systems of systems perspectives to enable insights for sustainable and smart infrastructure systems.

Combining the technical, the practical and forward thinking, this research aims to create an approach to considering change and potential consequences – not only in infrastructure, but in society, in technology, in governance, and in the environment. Capturing the ripple effect of systems thinking, the research demonstrates how developing methodologies, frameworks, and thoughtful use of data brings benefits to people and enables societies to flourish. Importantly, this approach supports life cycle thinking across the three key sustainability dimensions – economic, environmental and societal.

Project purposes and outputs

This project aims to identify the requirements and needs of future smart infrastructure systems (1) to identify the applicability of digital twins in the infrastructure industry, and (2) to propose data-driven methods for better decision-making for smart infrastructure. Dr Didem Gürdür Broo is CSIC lead researcher for several projects working to these ends.

Future smart infrastructure and built environment systems

To understand how the United Kingdom's infrastructure and built environment may look in 2040, Dr Gürdür Broo invited 16 researchers from the Centre for Digital Built Britain to work together on identifying important trends, discuss their viewpoint on future directions, merge their thoughts and construct future scenarios. The aim of this project was to derive a series of strategies to deal with urgent sustainability requirements while considering not only the present but also the future of the industry.

Applying forward thinking to planning and designing our built and natural environments highlights how decisions made today have direct and significant consequences for the type of world we build for generations to come. Framed by the climate crisis and written during the early months of the coronavirus pandemic, the outputs of the project, including the book *Four Futures, One Choice: Options for the Digital Built Britain of 2040*, explore the role of data to support and enhance sustainability and equality – and the potential of the UN Sustainable Development Goals to shape the built environment world of the future. The outputs are a wake-up call to academics, industry leaders and everybody else. An interactive e-book developed for children and based on *Four Futures, One Choice* was published in March 2021. For more information visit www.cdbb.cam.ac.uk/fourfutures.

Digital twins in infrastructure

Dr Gürdür Broo interviewed a number of executives and leaders from the infrastructure industry who are engaged with digital transformation and digital twins. The interviews and the result of the study aim to understand how applicable the digital twins concept is to the infrastructure industry, what the current practices are, what challenges it has in common with other industries and which obstacles are specific to the infrastructure industry.

The output of this project focuses on understanding how to create value with digital twins in infrastructure business models and develops strategies to put digital twins into effect in the infrastructure industry.

Data-driven sustainable infrastructure

Using data as an engineering tool, this research aims to create sustainable and smart infrastructure systems to drive digital transformation. It explores how data-driven approaches can turn passive infrastructure assets into cyber physical systems – the seamless integration of computation and physical processes with feedback loops – to enable sustainable and resilient decision-making. This thinking is being applied to real-life projects through digital twin implementations, including CSIC's Network Rail Staffordshire bridge digital twin demonstrator and Highways England integrated monitoring system (acoustic emission sensors, fibre optics, computer vision and cloud-based data platform), and is aligned to the Centre for Digital Built Britain's National Digital Twin programme. As such, this approach supports the capabilities of future infrastructure systems to be connected, enabling assets such as bridges, railways and transport systems to share data, aiding better decision-making that ultimately delivers benefits to all stakeholders.

While information provides the key to designing, building and living better, data does not come without challenges. This research proposes different ways to secure the right data and get it to the right person at the right time by considering data challenges – these include availability, accessibility, quality, volume, variety and longevity. Reaching this goal requires consideration of organisational structures that place data at the core of planning, designing, constructing, operating and integrating our built and natural environment. Better processes for data management procedures are key. It also needs the skillsets to support change and move beyond the gateway to analytics that data provides to embrace AI, emerging technologies and interoperability. A mindset shift to designing for people and with people, future-oriented thinking and a systems of systems perspective is an essential part of the mix.

Contact Dr Jennifer Schooling, CSIC Director
Team Dr Jennifer Schooling; Dr Didem Gürdür Broo

Computer vision beyond black boxes – all eyes on infrastructure and construction

Key benefits
- Understanding the benefits and risks of computer vision (CV) applications for civil engineering
- Identifying suitable CV solutions specific for infrastructure and construction use cases

The field of computer science that is computer vision (CV) brings focus to the creation of digital systems capable of processing, analysing, and making sense of visual data. Computers are programmed to process an image at a pixel level and understand it. Visual information can be retrieved and interpreted through special software algorithms.

Demystifying CV in infrastructure and construction to maximise value

This project applies CV algorithms such as object tracking, data segmentation and image matching to solve specific challenges on civil engineering projects to benefit engineers and ultimately all stakeholders. Potential use cases will be considered in order to assess the specific insights required by an organisation to ensure that CV is a suitable solution. Cost-effective solutions can deliver insights gained from using low-cost cameras and poor-quality images which, in some situations, may provide adequate data. This approach demonstrates the application of CV in infrastructure and construction without over-burdening budgets.

A rigorous assessment of the context for a CV solution and realistic expectation of capability is key to securing value from investment. There is a tendency for some CV projects to make assumptions such as overestimating the accuracy capability of artificial intelligence (AI) and expecting added value from a reduction in error and need for human intervention. In reality, AI relies heavily on labelling and data training which requires a lot of human resource.

Feedback from industry partners to CSIC researchers about experiences applying CV solutions to civil engineering projects has highlighted results falling short of expectations. This project considers the development of standardised descriptions and explanations of CV technology for the sector in order to; enhance understanding and support use of CV in infrastructure and construction, identify when use of CV is appropriate and better manage risk and expectation when planning a new CV approach. For this project CSIC researchers aim to; provide guidelines and a framework for using CV in civil engineering, and gather information from industry practitioners about what the real-world need is for CV and why it has not always worked well in the past.

Infrastructure and construction

The adaptability and wide range of applications for CV makes it potentially very well suited to a variety of civil engineering applications where different structures and sites present challenges for asset managers and developers. These challenges include: identifying people or hazards on a railway line; keeping track of site progress; making sure construction workers operate in a safe environment; supporting autonomous operations; and tracking defects in structures as part of a monitoring system. CV for infrastructure and construction is attracting a number of start-ups developing solutions for the sector.

Other useful applications of CV involve monitoring to assess the best locations for a construction site by analysis of the surrounding environment, the maximum output of renewable energy by measuring shade exposure or dirt collected on solar panels, the heat profile of a house or building to optimise energy use, and the risk of environmental events, such as flooding and landslides, allowing asset managers and local authorities to better prepare themselves.

Opportunities and limitations

The full potential for CV in civil engineering is currently underexploited. CV-based technologies are often limited to capture, such as CCTV, recording a condition or generating a 3D model, without further processing to assess quality and produce additional value. CV is an adaptable and cost-effective approach and there may be lessons learned from CV solutions applied to other sectors useful to infrastructure and construction organisations. As a relatively new field of technology within infrastructure and construction, some organisations rely on short term projects to test a CV solution. However, without an adequate understanding of both the opportunities and limitations of these technologies, they risk a disappointing return on investment.

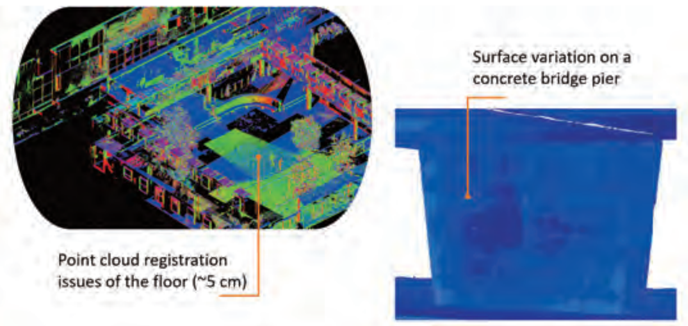
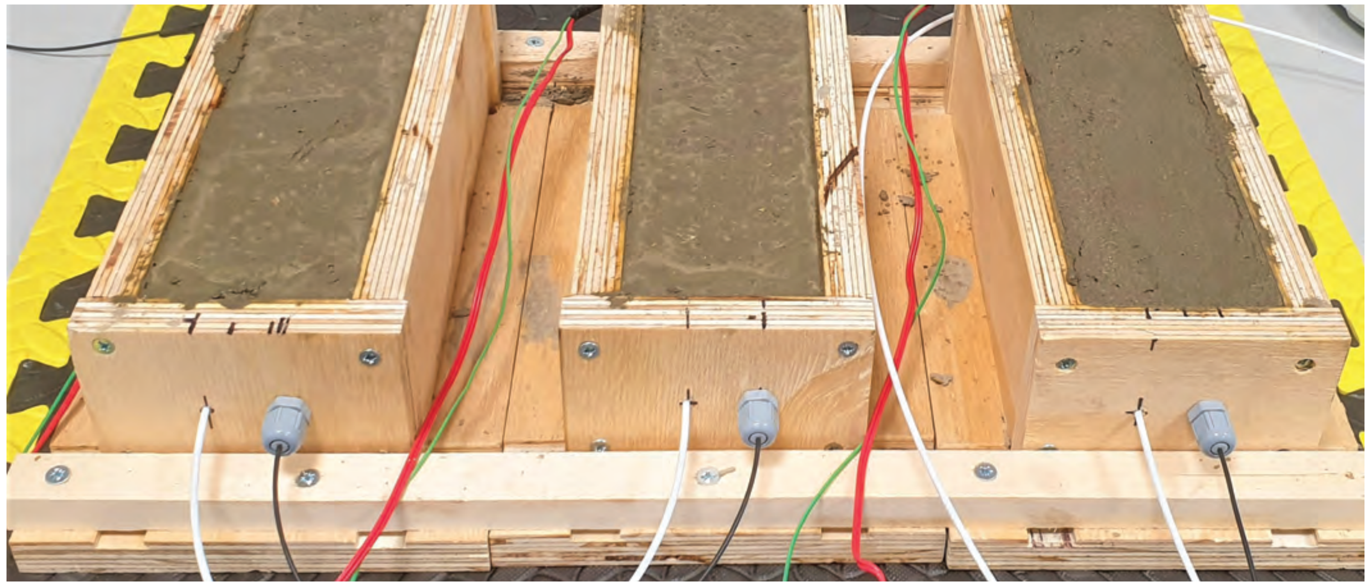


Figure 1. The point cloud on the left shows local irregularities in geometry pointing out data preparation errors such as misalignment. The one on the right shows surface variation of a bridge pier that can be monitored over time to spot abnormal behaviour.

Contact Professor Joan Lasenby
Team Professor Joan Lasenby; Vladimir Vilde

Inside concrete



Concrete samples with embedded fibre optic sensors to measure strain and temperature

Key benefits
- Enabling resource-efficient decision-making
- More efficient utilisation of concrete

This project will generate new data on concrete to enable engineers to make resource-efficient decisions to support the longer-term goal of creating more sustainable structures. Concrete is associated with high carbon dioxide emissions – construction accounts for nearly half of the UK's carbon emissions, and cement/concrete manufacture alone for four to eight per cent of global CO_2 emissions[1]. This project seeks to mitigate future inefficiency by capitalising on improved concrete performance data.

Researchers are investigating fibre optic sensor (FOS) systems embedded in concrete to better understand performance. FOSs allow a continuous collection of data along the fibre length instead of at single pre-selected measurement points as would be obtained with traditional temperature or strain sensors. This enables a better evaluation and assessment of the integrity of a concrete structure. For instance, the temperature development in fresh concrete during hardening can be used to infer the concrete strength gain over time and local strain increases, which can be an indicator of crack formation, can be identified anywhere along the FOS sensor.

Current FOS systems have several limitations including a lack of interpretation models for an in-depth understanding and difficulties in meeting different stakeholder priorities. Professor Janet Lees, who leads this project, chaired a session at the 2019 CSIC Partner Strategy Day with industry colleagues considering how to make better predictions of concrete strength based on early-age measurements. Topics discussed included the need to reconcile in-situ concrete quality with the original specification which requires better confidence in concrete quality at the early stages of the curing process. The chemical reaction between cement and water that binds sand and gravel together to make concrete takes typically 28 days to reach its design strength. Controlling the moisture content and the temperature of new concrete for the first several days through curing is essential to ensure the desired structural integrity. This project is a step forward in harnessing the potential of FOS systems to make better predictions of concrete quality and strength during the curing process.

By casting continuous FOS sensors into fresh concrete, data will be captured as the concrete hardens. Collecting and analysing this data enables an evaluation of the in-situ versus designed properties. As a result, future concrete mixtures and structural designs can be optimised. For example, if a concrete mixture develops a higher strength than intended then either the concrete mixture can be adjusted to reduce the cement content and hence CO_2 footprint, or the structural element can be redesigned to use less material thereby leading to a lower embodied carbon. The information can also support more efficient construction programmes including the timing of formwork removal and first loading. Shorter construction times can also lead to reductions in resource consumption.

The experimental programme is being conducted within the University of Cambridge's state-of-the-art National Research Facility for Infrastructure Sensing (NRFIS) and is exploiting NRFIS equipment to achieve the research objectives. The enhanced data will lead to new understanding for the more efficient utilisation of concrete to thereby reduce the CO_2 impact.

Contact CSIC Investigator Professor Janet Lees
Team Professor Janet Lees; Dr Marcus Maier

[1]www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf

New interpretation framework technique for detecting anomalies in piles from Thermal Integrity Profiling (TIP) data

Key benefits

- Design verification of piles, potential project time and cost savings and reduction of material use

Detecting pile anomalies with thermal integrity testing

The need for larger and deeper foundations to support taller buildings, structures with large spans, and buildings in poor ground conditions is increasing. Although pile installation equipment and machinery continue to be developed, there are still challenges for the construction industry to overcome, including determining the as-built quality of the foundation piles. This is a crucial task that needs to be established immediately following the construction stage before the loads are applied. It assesses whether the pile foundations are constructed according to the design and, if that is verified, opens up the possibility for future pile reuse with better as-built records.

Traditional pile integrity testing techniques only provide data to assess a limited part of the concrete between and around access tubes with results that are very difficult to interpret. Some techniques even pose safety risks for operators. After pile installation, anomalies such as voids, soil intrusions or shaft collapse are very challenging to detect. The presence of these anomalies could compromise the structural capacity of the piles or cause severe durability issues.

Recently a new integrity test, Thermal Integrity Profiling (TIP), has been put to use in foundation construction, which measures temperature changes and thermal profiles of concrete during curing. Heat generation and dissipation of early-age concrete is determined by the concrete mix, the ground conditions and the shape of the concrete structure. If defects exist inside the concrete body, they will appear as local temperature variations when compared to the expected heat generated during curing. This new technique of TIP does have limitations, however. The current data interpretation practice is primarily based on experience. Anomaly detection through direct analysis of temperature profiles is currently indicative or suggestive, and temperature signatures are usually similar and numerous causes are not easily isolated. The core principle of the TIP testing technique – collecting detailed temperature measurements along the pile during the hydration process – is promising, but a new interpretation approach is required.

A new interpretation framework for TIP data

CSIC researchers have developed a new interpretation framework (Figure 1) for TIP data. The framework follows a staged investigative process to establish and assess anomalies in the problematic regions along the pile employing the combined use of detailed finite element (FE) simulations, the actual temperature data from TIP and generic evolution algorithms.

These algorithms will be used to calibrate the cement hydration model and minimise the cost function for identifying defects. At each stage, more details can be revealed about the anomalies being investigated including, crucially, location, size and shape. This staged process enables practitioners to follow a risk-based approach and decide whether or not to pursue subsequent stages of construction depending on the results they get at the end of each stage.

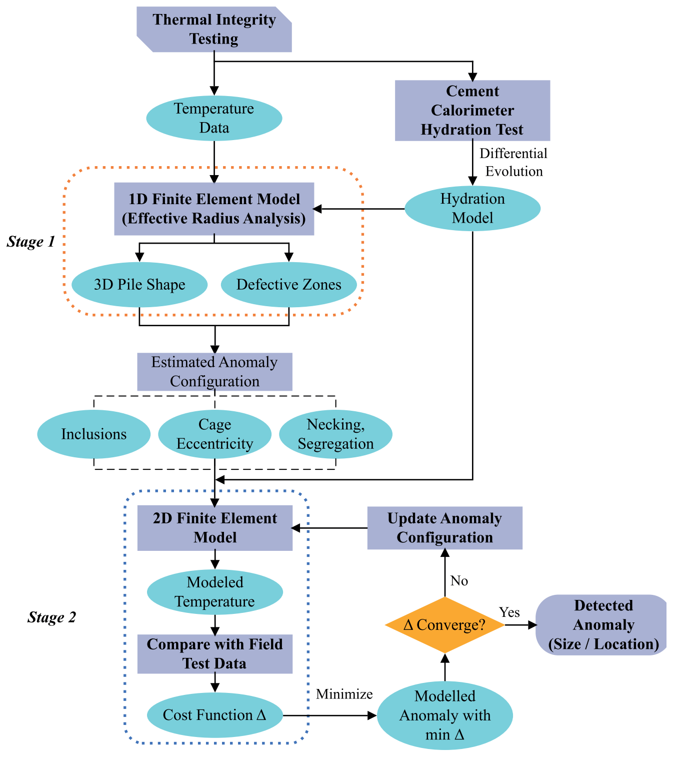


Figure 1. TIP data interpretation framework.

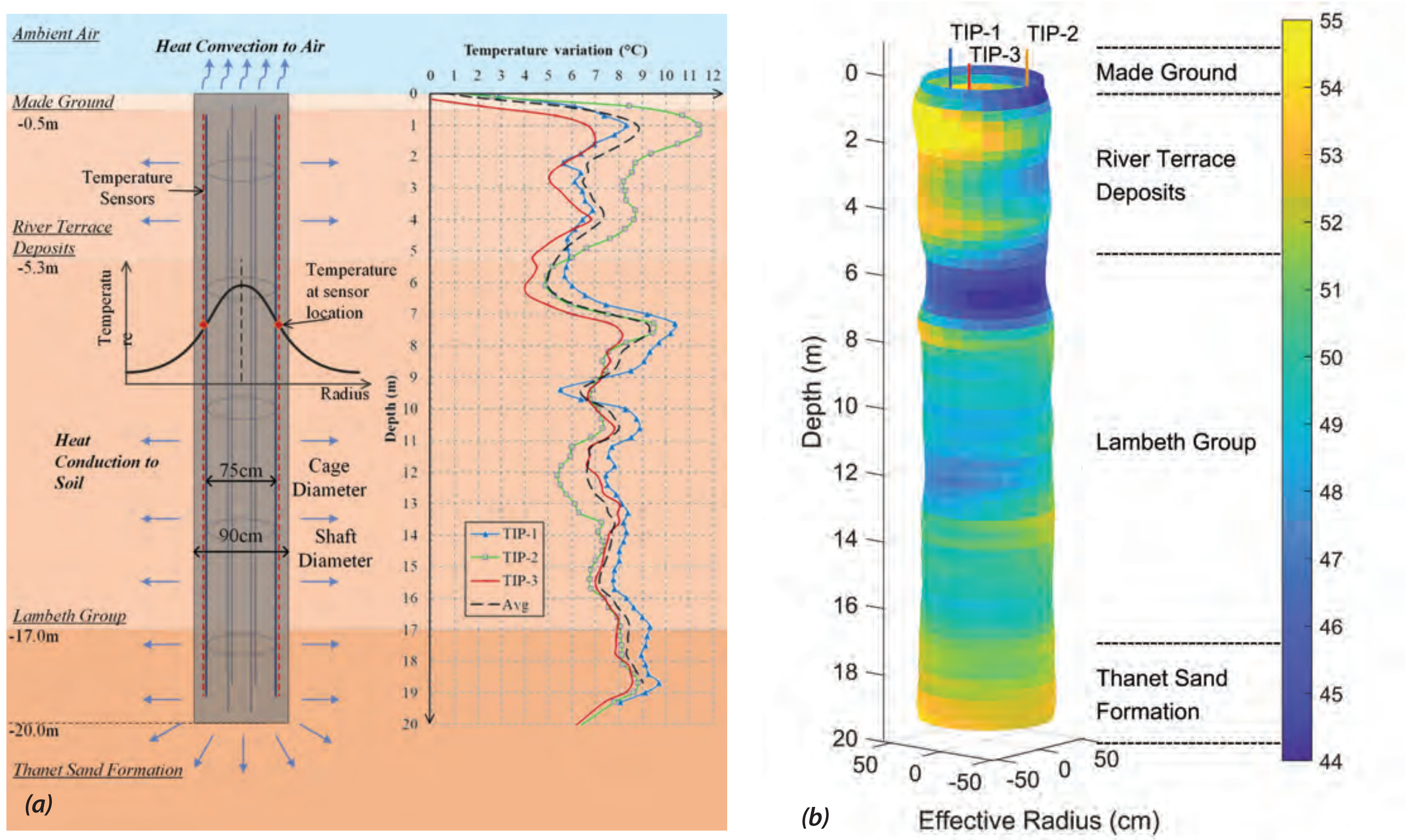


Figure 2. (a) Designed pile and recorded temperature profiles, (b) Generated 3D pile shape.

Field testing

In collaboration with CSIC partners, Arup and Cementation Skanska, a thermal integrity test was conducted onsite for a continuous flight auger pile instrumented with temperature sensor cables. Figure 2(a) shows the designed pile, the ground conditions and temperature profiles along three cables at 17 hours after concrete placement. The data shown in the figure are changes compared to the initial baseline temperature recorded. Following the new approach, the temperature change profiles as shown in Figure 2(a) were used to generate a 3D pile shape (Figure 2(b)), for more intuitive identification of problematic regions. The orange colour indicates an expanded pile radius (larger than the average 0.50m radius), and the blue colour represents a contracted pile radius (smaller than 0.5m), which needs further investigation. A series of finite element analyses (following Figure(1)) were then conducted systematically on the suspected problematic regions to determine the actual size and location (within the cross-section of the pile) of the anomaly. The researchers found that the new TIP interpretation approach could predict the size and location of an anomaly with high accuracy. The errors between predicted defects and pre-built reference defects are within four per cent of the cross-sectional area.

Laboratory testing

The CSIC team have also been conducting laboratory thermal integrity tests at the Schofield Centre in Cambridge. These tests have provided further results to answer some crucial questions including the optimal time to conduct analyses for the potential defects and the minimum defect size that the specific TIP testing techniques used on site could realistically identify.

The results from field trials and laboratory tests have shown great potential of using this approach for fast and accurate defect detection. This new approach, depending on the stages required for the analysis, will potentially provide practising engineers with crucial test results about the quality of the pile immediately following pile construction, hence enabling immediate repair and remedial work at a lower cost.

Next steps

The team will work with industry partners on more field trials to verify the detectability in different field conditions. Researchers expect that this thermal integrity approach could potentially become a standard quality control approach in the industry within a few years. In the meantime, a software prototype for thermal integrity test data analysis will be developed by CSIC for use by industry practitioners.

Contact CSIC Director Dr Jennifer Schooling; CSIC Investigator Dr Mohammed Elshafie
Team Dr Jennifer Schooling; Dr Mohammed Elshafie; Jason Qianchen Sun

Closing the loop: Back analysis of sprayed concrete tunnel junctions

Key benefits
- Validation of design, improving construction safety, reducing material use and associated carbon, saving time and money

Original instrumentation at Liverpool Street station
In 2014, CSIC led groundbreaking work instrumenting and monitoring two junctions in a large sprayed concrete lined (SCL) tunnel with distributed fibre optic sensors (DFOS) to observe the changes in strain in the lining during the construction of cross-passages[1]. This was carried out at the Crossrail Liverpool Street station (Queen Elizabeth Line) in London to gather data on the behaviour of the tunnel lining during the breakout and excavation of the cross-passages. The goal was to produce reliable field data to investigate the accuracy of the 3D numerical models used to design the cross-passage junctions. In particular, the response of the reinforced thickening layer of SCL added at the tunnel enlargement chambers at cross-passage junctions was investigated with the aim of exploring the possibility of reducing material use and the associated carbon, which would also save time and money as well as enhancing safety during construction.

Designing SCL tunnels
SCL tunnels are challenging to design, especially the junctions, because of the complex material behaviour of the sprayed concrete and the ground, the multi-stage construction sequence and the dearth of available monitoring data from existing tunnels. The designers on the Crossrail project used sophisticated 3D numerical models to design these junctions but were aware of limitations in the modelling and some results did not tally with data collected from real tunnels. The resulting design was believed to be conservative in some respects which prompted the installation of the CSIC distributed fibre optic sensor system.

Understanding SCL performance from monitoring data
The DFOS monitoring data indicated that the load redistribution within the tunnel SCL during the cross-passage excavation was localised and significant changes in strain were limited to a relatively short distance from the cross-passage openings (1-2m) – smaller than the extent of the thickening SCL. These findings suggested that the need for thickening the SCL layer diminishes rapidly with increasing horizontal distance from the cross-passage openings. This implied that the tunnel enlargement chambers at cross-passage locations could be reduced in length, leading to safer construction and significant savings in material use. However, while the general observed mode of deformation matched expectations, the detailed pattern of recorded strain was not always consistent with design predictions and further research is required.

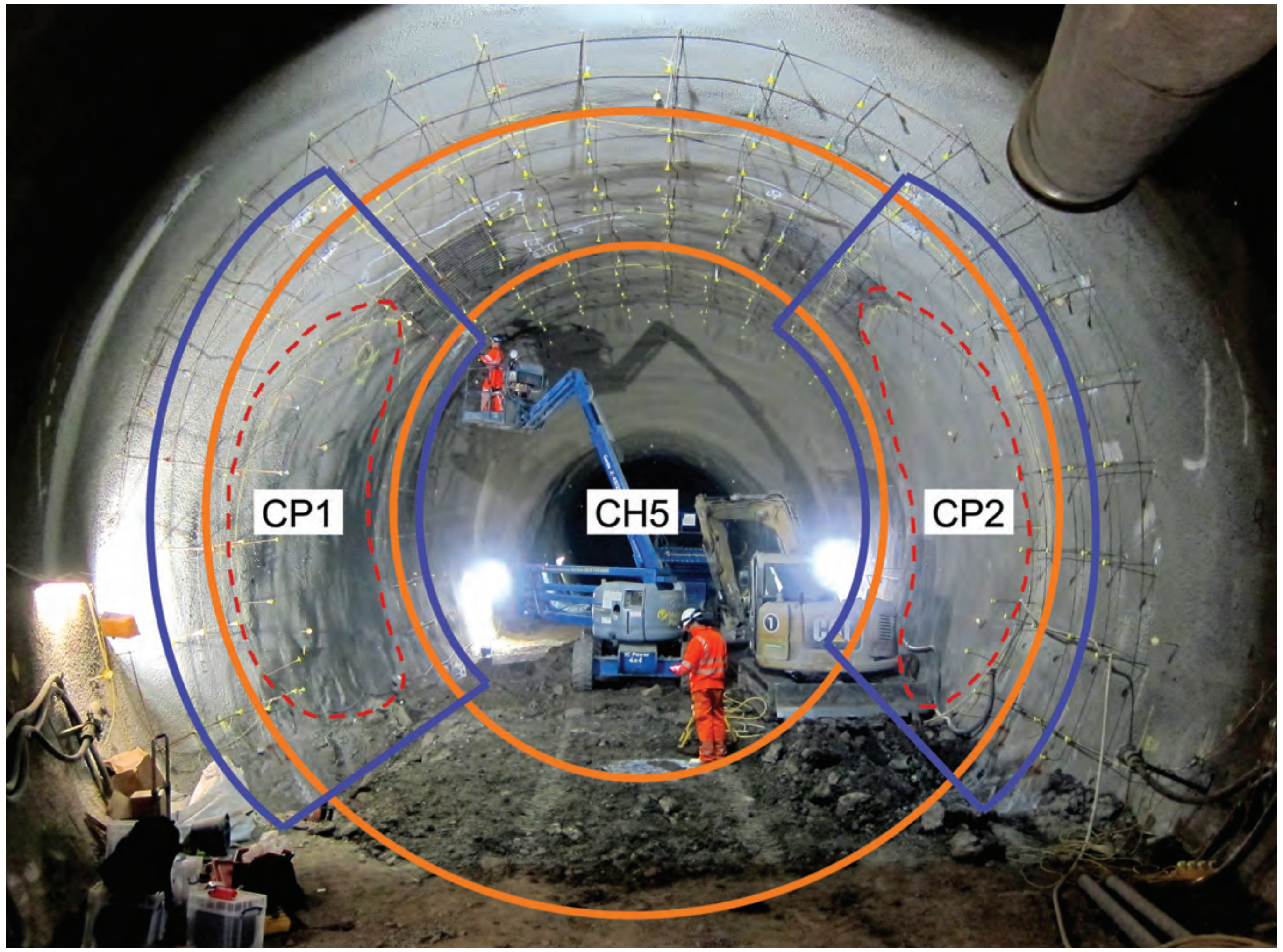
Closing the loop
To realise the full value of these high-resolution measurements, back-analyses and comparison of measurements with current design methods is required. A CSIC secondment project, which started in December 2020 with secondee Dr Alun Thomas, an established authority in sprayed concrete design and a member of the original Crossrail station tunnel design team, builds on the original research and aims to close this loop. With first-hand knowledge of the tunnel design, Dr Thomas has built a sophisticated 3D computer model of the junction to calculate the stresses and strains in the lining. New 3D models will be run to test the impact of possible enhancements of the modelling such as nonlinear behaviour of the concrete, bonding between sections of the tunnel and the bond of the lining to the ground.

By comparing the 3D computer models with the fibre optic data collected in 2014, the research team, which includes CSIC researchers from the original instrumentation project, plans to investigate how to make the design predictions more accurate and to feedback into design guidelines.

Modelling and analyses
Most of the computer modelling has been completed and researchers are now analysing the results. At this early stage there appears to be better agreement between the more sophisticated design models and the measured results, indicating scope to improve the design methods, potentially leading to a reduction in the quantity of concrete and reinforcement required.

The investigation has also revealed some limitations in the original monitoring as well as a number of unanswered questions about the design of the tunnels which lead from a tunnel junction ('child' tunnels). Researchers are looking for opportunities to instrument other tunnel junctions with DFOS and further computer modelling is planned to investigate the behaviour of child tunnels. Full results from this secondment will be presented in journal papers which are planned for submission during the second half of 2021, including descriptions of the comparison between current design methods and the original CSIC monitoring data and identification of areas for improvements and suggestions for better design methods.

Benefits to industry
Tunnels are an important part of major infrastructure such as Thames Tideway, HS2 and the Lower Thames Crossing and SCL is a widely-used method. The tunnelling industry and the many sectors which use tunnels will benefit from improvements to the construction of cross-passage junctions since this will result in more economical use of materials including steel and concrete, a reduction in the associated embodied carbon, an improvement in construction safety and a reduction in project time and costs. In addition, a better understanding of the factor of safety in these structures enables the impact on neighbouring structures to be minimised, which is an important consideration when tunnelling in urban environments. With increased urbanisation internationally, improvements in the design of cross-passage junctions could provide benefits at scale.



CSIC embedded a DFOS system within the thickened SCL in enlargement chamber CH5 at two cross-passage junctions, CP1 and CP2, in order to monitor the changes in the distributed strain profile that occurred in the tunnel lining during the excavation. The DFOS circuits within the SCL at cross passages CP1 and CP2 are indicated by the two rings (orange) and two rectangles (blue)

Contact CSIC secondee Dr Alun Thomas, MD of All2Plan Consulting ApS
Team Professor Giulia Viggiani; Dr Mohammed Elshafie; Dr Alun Thomas; Dr Nicky de Battista
Industry Crossrail Ltd; contractor BBMV JV; designer Mott MacDonald

[1]de Battista, N., Elshafie, M.Z.E.B., Soga, K., Williamson, M., Hazelden, G., Hsu, Y.S., 2015. Strain monitoring using embedded distributed fibre optic sensors in a sprayed concrete tunnel lining during the excavation of cross-passages. Proceedings of the 7th International Conference on Structural Health Monitoring and Intelligent Infrastructure (SHMII7). Torino, Italy.

Impact and outreach through the decade

CSIC's core agenda has been driven by a collaborative vision, creating solutions to industry challenges by working with companies that share our vision of change. Sharing information, skills and knowledge is key to advancing industry adoption of innovative solutions to engineering challenges. CSIC has worked at a number of levels to engage with a range of audiences and invite interest in its work including industry-focused knowledge exchange events, research presentations, and public lectures. As well as hosting workshops, lectures and training, CSIC experts are regularly asked to contribute to panels and industry events. Select examples of the outreach and impact CSIC is delivering to shape the strategic agenda for smart infrastructure and enable its implementation in practice are outlined below.

Sharing information skills and knowledge through industry focused events

CSIC has held a wide range of industry knowledge exchange events throughout the last 10 years. In the past year our programme of events included:

- CSIC Partner Gathering – this annual event was held online in September 2020 and brought together industry and academia for a series of short presentations on current CSIC research and innovations.
- Digital Cities for Change Emerging Connections Workshop – the fourth in a series, this workshop event held over two sessions online in October 2020 saw policy makers, academics and industry professionals come together to inform the development of a Competence Framework for city managers in the digital age.
- Partner Strategy Day – this annual event attracted more than 50 participants from partner organisations to discuss how CSIC's future research agenda – focused on smart infrastructure in the context of the grand challenges of net zero carbon, resilience and resource efficiency – can bring value to partner organisations.
- Computer Vision Workshop 'Beyond black boxes' – held in February 2021, this online workshop covered challenges and opportunities for civil engineering in the selection, installation and processing of computer vision techniques.
- Digital Cities for Change seminar series – this annual series seeks to demonstrate how built-environment data and digital tools can be used to inform better and more cohesive decision-making to help improve city planning, management and the delivery of public services. The 2021 seminars will take place in autumn.
- Bi-weekly research presentations – current CSIC projects and activities delivered by CSIC researchers and collaborators. The presentations moved online in spring 2020 and are now available to view on YouTube.

CSIC secondee presents poster at a partner event

CSIC celebrates 10 years – a series of online events organised during June and July 2021 to Celebrate 10 Years of CSIC. Events included: In Conversation with CSIC Director Dr Jennifer Schooling and Professor Mark Girolami, Sir Kirby Laing Professor of Civil Engineering and academic lead of CSIC, looking ahead to discuss the future of digitalisation and the built environment; a series of short and fast-paced presentations from CSIC researchers on current projects; and Bringing Buildings to Life, presenting a web hub to interact with 3D models of instrumented areas of the Civil Engineering Building and visualisations of the data. The celebratory events culminate with the CSIC Distinguished Lecture 2021.

Industry partners in discussion at CSIC Partner Strategy Day

International Conference on Smart Infrastructure and Construction (ICSIC)

In 2016, CSIC founded the International Conference on Smart Infrastructure and Construction (ICSIC) in Cambridge. The three-day event brought together leading experts from across the world including academics, practitioners and policy makers from infrastructure planning, construction, asset management, smart cities and sensing. The second ICSIC, held in 2019, was attended by more than 200 delegates and

CSIC online team meeting

included 80 presentations, workshops, a conference exhibition and poster area displaying some of the latest innovations in smart infrastructure and construction. Keynotes as well as a number of presentations from this conference are available to watch on CSIC's YouTube channel. Proceedings of ICSIC 2019 are available from the ICE Bookshop. The next conference will be held at the University of California, Berkley in 2023.

Distinguished Lecture series

CSIC launched a Distinguished Lecture series in 2013 with the inaugural lecture given by Professor Tom O'Rourke, Chair of the CSIC International Advisory Group, on 'The New Normal for Natural Disasters'. Over the years CSIC has welcomed many leaders in their fields to present the Distinguished Lecture,

ICSIC keynote

most recently CSIC International Advisory Group member, Professor Jerome P Lynch, from the University of Michigan on 'The role of the civil engineer in an increasingly automated infrastructure world'. The 2021 lecture by Professor Jim Hall from the University of Oxford considers 'The data revolution in global-scale analysis of climate risks to infrastructure systems'. All lectures can be viewed on the CSIC website and YouTube channel.

Sustainability and carbon zero roundtables

CSIC hosted a roundtable discussion during the 2018 Global Engineering Conference (GEC) at the Institution of Civil Engineers in London to explore exploiting data as an engineering tool to mitigate climate change. The paper, 'Smart Sustainability', summarises the discussions at the event. A second roundtable, including infrastructure clients, contractors, consultants and policy makers was held in March 2020 to develop pragmatic actions around achieving zero carbon in infrastructure and construction in the short and medium term, and provide support and guidance to policy makers. The roundtable group continues to meet and has developed a *Carbon Reduction Code for the Built Environment*, for use by clients, consultants, contractors and supply chain members across all sectors of the built environment. The Code is being trialled by the Environment Agency, HS2 (through the Skanska-Costain-Strabag joint venture), and the National Association of Construction Frameworks. Initial results, including trial case studies, were highlighted at an online event on 17 June 2021 launching the first issue of the Code.

Sharing information skills and knowledge through media

Smart Infrastructure Blog

In 2020 CSIC launched the Smart Infrastructure Blog, a monthly multi-disciplinary blog series published on the CSIC website and showcasing opinions and ideas from the forefront of smart infrastructure and construction. Topics have ranged from making the case for a socio-technical approach in cities, risk and resilience, transport infrastructure asset management, to making a digital mindset front and centre of business, engineering and decision-making. CSIC is very grateful to all the contributors who come from a wide range of organisations including CSIC, Costain, HS2, and Innovate UK.

Print and online media

CSIC research has regularly featured in the national, regional and trade press over the years including the following online and print publications: Financial Times, BBC Click, Infrastructure Intelligence, New Civil Engineer, Civil Engineering Surveyor, Ground Engineering, BIM +, Geospatial Engineering, Royal Institute of Chartered Surveyors (RICS) Construction Journal, The Conversation, Microsoft On the Issue, Ordnance Survey's Everything Happens Somewhere, Beyond BIM podcast, Institute of Chartered Accountants in England and Wales (ICAEW) Viewpoint series, The Structural Engineer Journal, World Tunnelling Magazine, Tunnels and Tunnelling, RICS Modus magazine, Materials World, Electro Optics, and BBC Radio Cambridgeshire.

Website and social media

More than 40 case studies, featured on the CSIC website, present solutions to challenges faced by industry on a range of infrastructure projects concerned with both new and existing assets. The CSIC YouTube channel includes over 60 presentations on smart infrastructure and construction projects with more than 20K views of our videos. These presentations and case studies bring focus to the use of data as an engineering tool to enable smarter decisions about the design, build and management of our infrastructure.

Influencing policy and industry practice

CSIC works with policy makers, regulators and clients to influence policy and create the market which incentivises industry to adopt smart infrastructure solutions. Examples include: the 'Smart infrastructure solutions in the transport sector' paper for the DfT; best practice guides written by CSIC research associates and investigators and published in 2016 by the Institution of Civil Engineers (ICE), which cover the installation and operation of novel sensing technologies across the fields of asset monitoring and management; the paper 'Intelligent Assets for Tomorrow's Infrastructure: Guiding Principles', sets out the need for an alternative view on the management of infrastructure assets; and, our facilitation and contribution to the delivery of the series of position papers: 'Smart Infrastructure', 'The Gemini Principles', 'Flourishing Systems', and 'Smart Sustainability'. These documents have all generated further action by clients, policy makers and the supply chain.

Institution of Engineers (ICE) State of the Nation Reports

CSIC has contributed to a number of ICE State of the Nation series of reports. Dr Jennifer Schooling, Director of CSIC, was a member of the State of the Nation Steering Group for the 2017 (State of the Nation 2017: Digital Transformation) and the 2020 (State of the Nation 2020: Infrastructure and the 2050 Net-Zero Target) reports. The 2020 report outlined actions and policy interventions recommended to encourage the sector – and the UK economy more widely – to move towards net zero.

NIC Technology Study

CSIC responded to the National Infrastructure Commission's (NIC) Technology Study Call for Evidence in 2016 making the case for smart infrastructure. The NIC included a CSIC project case study in the subsequent NIC report 'Data for the Public Good' and, also in the report, recognised CSIC as one of the institutions "integral to the digital framework" for data on infrastructure.

Centre for Digital Built Britain

CSIC is aligned with and works in collaborations with the Centre for Digital Built Britain (CDBB). CSIC Head Prof Lord Robert Mair was instrumental in the creation of CDBB and chairs its Strategic Board. Director Jennifer Schooling sits on the Digital Framework Task Group, the body overseeing CDBB's major initiatives around development of an information management framework for the built environment.

Industry secondment programme

CSIC runs an industry secondment programme, part-funded by industry, where staff from partner organisations work closely with CSIC to develop and adopt research outputs into commercialisation. Secondees bring new skills, projects and challenges to CSIC that help to develop emerging tools and technologies for industry use. Over the last six years, CSIC has hosted more than 25 secondees who gain a deep understanding of innovations which they can apply for the direct benefit of their own companies/organisations.

CSIC researcher demonstrating a project at the Cambridge Science Festival

CSIC researchers and guests at the International Conference on Smart Infrastructure and Construction

Sharing smart infrastructure with the public

CSIC has also contributed to a number of public events including the University of Cambridge Science Festival, the Hay Festival, the ICE Library exhibitions, including the 'Tunnel Engineering' and 'Invisible Superheroes' exhibitions, and the Ove Arup 'Catalyst for Change' exhibition. CSIC's public event 'Smart Building, Smart Construction' was part of the Department of Engineering's events at the Cambridge Science Festival presenting a number of smart infrastructure and data-driven innovations in collaboration with the Laing O'Rourke Centre for Construction Engineering and Technology. The 2021 event, renamed the Cambridge Festival and moved online, included two CSIC events: 'Bringing buildings to life – smart infrastructure at the Civil Engineering Building' and a presentation on 'Growing Underground', an urban farming project located in former WW2 air raid shelters 120ft below the busy streets of south London.

Awards and accolades

Industry awards

CSIC's research projects have been shortlisted for and have won numerous awards. Some highlights include:

- Fleming Award 2013 – the Lee Tunnel, Abbey Mills, Stratford – Shaft F project
- Ground Investigation and Monitoring Award – Tunnelling and Underground Space Awards 2014 for The Smart Tunnel
- Editor's Award at Ground Engineering Awards 2016 – development of CemOptics, Cementation Skanska and CSIC
- New Civil Engineer Tunnelling Award for Innovation 2018 – CSIC Fibre Bragg Grating-Based Real-Time and Low Maintenance Strain Monitoring of Existing Assets
- Best Use of Technology at Rail Partnership Awards 2019 – CSIC project Smart Railway Infrastructure (Hooley Cutting)
- New Civil Engineer TechFest Rail Visionary 2019 – CSIC Structural Health Monitoring of Ageing Railway Infrastructure
- Innovation in Tunnel Fit-Out, Operations and Maintenance Award – CSIC Growing Underground, New Civil Engineer (NCE) Tunnelling Festival Awards 2019.

Awards for academic papers

CSIC researchers and academics have published more than 1500 papers. A number of papers authored and co-authored by CSIC academics have won accolades and awards, including: the 2015 Institution of Civil Engineers' (ICE) Russell Crampton Prize; the 2017 Telford Premium Prize; and the 2019 James Croes Medal from the American Society of Civil Engineers (ASCE) among others.








Our people

Leadership

Professor Lord Robert Mair CBE
Founding Head of CSIC
Dr Jennifer Schooling OBE
Director of CSIC
Professor Mark Girolami
Academic Lead of CSIC

International Advisory Group

Professor Michael Batty CBE
University College London
Professor Yozo Fujino
Yokohama National University, Japan
Professor Jerome P. Lynch
University of Michigan, USA
Dr W. Allen Marr
Founder and CEO of Geocomp
Professor Thomas O'Rourke (Chair)
Cornell University, USA
Professor Bill Spencer
University of Illinois, USA
Professor Hehua Zhu
Tongji University, China

Steering Group

Simon Abbot
Network Rail
Karen Alford
Environment Agency
Dr Keith Bowers
COWI
Professor John Burland CBE (Chair)
Imperial College London
Volker Buscher
Arup
Robert Dean
HS1
Tim Embley
Costain
Mark Enzer
Mott MacDonald
Tom Foulkes
Independent Consultant
Steve Hornsby
Independent Consultant
Adam Locke
Laing O'Rourke
Professor Gordon Masterton
University of Edinburgh/UKCRIC
Professor Andrew McNaughton
HS2
John Pelton
Jacobs
Richard Ploszek
Infrastructure and Projects Authority
David Pocock
Jacobs
Stephen Pottle
WSP
Phillip Proctor
Highways England
Professor William Powrie
University of Southampton/UKCRIC
Michael Spencer
International Association of Engineering Insurers (IMIA)
Dr Scott Steedman CBE
British Standards Institution (BSI)
John St Leger
HS2

We would like to thank everyone who has contributed to 10 years of CSIC, our Partners, International Advisory Group, Steering Group, current and former staff. In particular we would like to thank Steering Group members Professor John Burland, Tom Foulkes, Stephen Pottle and John Pelton for their invaluable input to this Review.

The CSIC diaspora

Over the years CSIC has attracted a wide range of talented researchers and students who have all contributed to making the Centre what it is today. To mark 10 years of CSIC, a number of the CSIC diaspora reflect on their time as part of the team.

Asal Bidarmaghz
Lecturer in Geotechnical Engineering, School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia – at CSIC 2017-2019
"I worked on a project exploring the utilisation of underground spaces with focus on the ground sustainability and efficiency to identify patterns of energy consumption and alternative geo-energy sources. What I enjoyed the most about my time at CSIC was the excellent level of industry engagement in projects. This made me feel that my research was solving a real-life problem and was very impactful. The connections I made and the initiatives I was involved with have been the basis of my current academic career in Australia."

Claudio Martani
Lecturer and Research Associate at the Infrastructure Management Group, ETH Zürich (Swiss Federal Institute of Technology), Switzerland – at CSIC 2013-2015
"While at CSIC, I worked to develop a method for minimising the risk in construction through flexible design (or option embedded design) solutions. I also worked on crowd monitoring and modelling techniques. All my current research and teaching on 'future-proof design' builds on the use of both the real-options methodology and the 'sensing and responding' built environment that I began exploring and deepening during my time at CSIC."

Matt DeJong
Associate Professor, Ray & Shirley Clough Presidential Chair in Structural Engineering, University of California, Berkeley – at CSIC 2016-2018
"Through CSIC, I had the opportunity to work on numerous projects related to laser scanning and fibre optic monitoring of infrastructure and historic structures. From the bigger picture perspective, I enjoyed being part of the current digital transformation that CSIC is helping to enable. More specifically, I thoroughly enjoyed the challenge of collecting and interpreting data from real buildings and bridges, which certainly stretched our modelling abilities and led us to question many existing assumptions. Personally, and most importantly, I enjoyed working with many great people at CSIC and being part of a truly collaborative team."

Viorica Patraucean
Research Scientist for Google's DeepMind – at CSIC 2014-2016
"My project aimed at extracting (3D) BIM models for already-built bridges to facilitate detecting changes in the structure of a bridge to inform maintenance decisions. I was involved in all the phases of the project, from extracting point clouds of real bridges using a laser scanner to modelling the data using various techniques. I enjoyed the diversity of tools I learned to use and create, and the diversity in backgrounds of the people I interacted with during the project."

Sinan Açikgöz
Associate Professor at the University of Oxford – at CSIC 2014-2018
"I worked on various applications of structural health monitoring on masonry assets. I enjoyed the exciting opportunities to work together with industry, the freedom to explore, the wonderful collaborations, and the many friendships. I owe my research independence to the trust and support that CSIC afforded me at such an early stage of my career. I take inspiration from the team at CSIC as I am building a new research group at Oxford."

Njemile Faustin
Senior Geotechnical Engineer, AECOM, London – at CSIC 2011-2017
"During my time at CSIC, I carried out research to improve the performance-based design of circular shafts. I enjoyed CSIC's collaborative work culture, the freedom to develop and test ideas and the opportunity to meet and learn from industry and academic leaders and a diverse group of people. It was inspiring to be part of a dynamic and knowledgeable team that is at the forefront of using innovation and data to provide smarter, sustainable infrastructure for us to enjoy. I also learned the importance of communicating effectively and this skill has helped me to navigate a career path at AECOM, a large global infrastructure consulting firm."

Hyung-Joon Seo
Lecturer at University of Liverpool – at CSIC 2013-2016
"My research related to the development and application of fibre optic sensors and laser-scanning technology. I learned so much while working at CSIC – knowledge about smart monitoring which is still the basis of my research, and interdisciplinary research methods by working with people from different engineering departments. My time at CSIC laid the foundation for my knowledge, thinking, and way of living as a researcher."

David Rodenas Herráiz
Senior Wireless Software Engineer at Ocado Technology – at CSIC 2014-2019
"I jointly worked with the Department of Computer Science and Technology, the Engineering Department and CSIC on the design, development and application of novel sensor technology with capability to send data wirelessly. I was also responsible for producing one of the CSIC best practice guides, related to wireless sensor network technology. Professionally, I enjoyed the opportunity to collaborate with several CSIC Industry Partners, working with other colleagues on many different research projects, and seeing some of the work on paper deployed and working in a real-world setting. There is much value in the outputs CSIC delivers and considerable expertise in the people who deliver that value. Getting to know and work alongside those people is definitely what I enjoyed the most."

Mehdi Alhaddad
Senior Geotechnical Engineer at Transport for London – at CSIC 2012-2017
"I worked on the influence of large infrastructure projects such as Crossrail tunnels on existing underground infrastructure using ground-breaking technologies. During this time, I developed a new monitoring system called CSattAR which was able to monitor deformation with paramount precision while costing a fraction of conventional systems and providing more detailed information. Working at CSIC gave me opportunity to work with great forward-thinking minds such as Kenichi Soga, Robert Mair and Jennifer Schooling and many more. I built a foundation in myself that was based on welcoming innovation and thinking outside the norms. What was great about CSIC was that we actually worked on the ground and made these new ideas a reality. This has shaped my attitude to innovation."

Bingyu Zhao
Postdoctoral researcher, University of California, Berkeley, USA – at CSIC 2014-2017
"I worked on city-scale pavement degradation analysis and traffic data analytics during my time at CSIC. I particularly enjoyed the opportunities to work with an interdisciplinary team, such as sensing, structures, geomechanics, simulations – it is an environment that is hard to find elsewhere. I think all my current research skills can be related to the training and time that I had with CSIC, from data analytics and computational techniques, to presentations and writing. From CSIC, I think the most valuable lesson for me is to appreciate infrastructure and our cities from a multi-disciplinary perspective."

Investigators

Dr Christelle Abadie
Lecturer in Civil Engineering
Dr Haris Alexakis
Lecturer in Civil Engineering, Aston University, University of Cambridge Visiting Academic Fellow
Dr Giovanna Biscontin
Lecturer in Geotechnical Engineering
Dr Ioannis Brilakis
Laing O'Rourke Reader in Construction Engineering
Dr Ruchi Choudhary
Reader in Architectural Engineering, Data-Centric Group Leader at The Alan Turing Institute
Professor Daping Chu
Head of Photonics and Sensors Group
Dr Matthew DeJong
Assistant Professor Structural Engineering, Mechanics and Materials, University of California, Berkeley
Dr Mohammed Elshafie
Associate Professor, Qatar University, University of Cambridge Visiting Fellow
Professor Mark Girolami
Sir Kirby Laing Professor of Civil Engineering, Programme Director for Data-Centric Engineering at The Alan Turing Institute
Dr Ying Jin
Reader in City Planning, Urban Design and Modelling
Professor Janet Lees
Professor of Civil Engineering
Dr Dongfang Liang
Lecturer in Civil Engineering Fluid Mechanics
Dr Kristen MacAskill
Lecturer in Engineering, Environment and Sustainable Development
Professor Lord Robert Mair CBE
Emeritus Professor of Civil Engineering, Director of Research
Professor Duncan McFarlane
Professor of Industrial Information Engineering
Professor Campbell Middleton
Laing O'Rourke Professor of Construction Engineering
Dr John Orr
University Lecturer in Concrete Structures
Dr Ajith Parlikad
Reader in Industrial Systems
Dr Jennifer Schooling OBE
Director of CSIC
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Isaac Newton Trust/Newnham College Research Fellow
Professor Ashwin Seshia
Professor of Microsystems Technology
Professor Kenichi Soga
Chancellor's Professor, University of California, Berkeley
Dr Sam Stanier
Senior Lecturer in Civil Engineering
Dr James Talbot
Senior Lecturer in the Performance-based Design of Structures
Professor Giulia Viggiani
Professor of Infrastructure Geotechnics
Dr Li Wan
Lecturer in Chinese Urban Development

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Reflections on CSIC

Professor Tom O'Rourke, Chair of the CSIC International Advisory Group, reflects on leadership and research.

The International Advisory Group (IAG) has met yearly since 2013 either at the University of Cambridge or, more recently, online. During this time, the group participated in the International Conference on Smart Infrastructure and Construction (CSIC) 2016 and 2019, which brought together world-leading academics and practitioners from the fields of infrastructure planning, asset management and sensing.

Throughout the years, the IAG has been impressed with CSIC's leadership, organisation, and research programme. The Centre's mission to transform infrastructure through smarter information has been driven by the senior leadership which consists of highly experienced and internationally recognised academics and experts in their field. The research programme is interdisciplinary and is composed of projects that were selected and prioritised with strong input from industry. The projects address important problems, with the great majority focused on technological innovations with strong potential for commercialisation. The projects provide sufficient diversity and depth to cover a broad spectrum of issues critically important for smart infrastructure and construction.

The successes of CSIC include various sensing technologies, data-driven asset management methods, as well as characterisation of city-scale transportation systems, energy consumption, and economic activity. CSIC innovations include: fibre optic sensors; infrastructure performance enhancement through wireless sensor networks; digital twin models for city-scale assessments; and structural health evaluations of critical infrastructure, such as bridges, rail, underground stations, foundations, and pipelines. The National Research Facility for Infrastructure Sensing (NRFIS) has been established at the Civil Engineering Building at the University of Cambridge West Campus. CSIC is now located at the Civil Engineering Building where the NRFIS facility offers substantial opportunities for both academic and industry research and full-scale experiments to advance sensing in the built environment.

The IAG recommendations have always been received earnestly by CSIC and implemented by both management and researchers. As CSIC celebrates 10 years of collaborating with industry partners, the IAG extends its best wishes for continued CSIC success.

Professor Tom O'Rourke is Thomas R Briggs Professor of Engineering in the School of Civil and Environmental Engineering at Cornell University. He is a member of the US National Academy of Engineering, International Fellow of the Royal Academy of Engineering, Distinguished Member of ASCE, and a Fellow of American Association for the Advancement of Science.

Professor John Burland reflects on 10 years of being Chair of the CSIC Steering Group.

The membership of the CSIC Steering Group is listed in this Annual Review and consists of distinguished representatives of the construction industry and public infrastructure sector together with key members of the CSIC leadership team and representatives from EPSRC, UKCRIC and Innovate UK. The first meeting of the Steering Group took place on 12 May 2011 and amongst those attending and still members of the Group were Steve Hornsby, Scott Steedman and myself. Tom Foulkes joined the Group shortly after the first meeting.

For the first two years much of the work of the Steering Group was devoted to reviewing, assessing and advising on a large number of collaborative Cambridge University/industrial project proposals for the first tranche of funding. These had been prepared by staff not only from the Engineering Department but also from Architecture, the Computer Laboratory and the Judge Business School. Thus, right from the start, the work of CSIC has been both collaborative and interdisciplinary and this has been a great strength and source of vitality.

Initially much of the focus of the work of CSIC was on the development and application of sensor technologies to the monitoring of infrastructure and construction with a strong emphasis on field demonstration projects. This has resulted in the publication of four important ICE published best practice guides together with invaluable education and training of construction professionals in sensing technology.

In recent years the work of the Steering Group has been not so much in advising on project proposals but much more on sharing experience and providing a forum for exploring future developments. To maintain the nautical flavour, I would say that our role has been not so much in steering but more the occasional touch on the tiller! I know that I speak for the whole Steering Group when I say that it has been a huge privilege to have shared in the work of CSIC. We have witnessed its development into a Centre of expertise of national and international standing which has a key role to play in bringing about much needed changes in the construction and management of infrastructure.

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