Imperial College London

The Centre for Systems Engineering and Innovation – 2030 Vision and 10-year Celebration

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The Centre: 2030 vision

"To achieve our 2030 vision, we advocate for an approach that sees the natural environment as all pervasive, where the built infrastructure is inseparable from it and is an adaptation of the natural systems to suit societal needs, using its materials and resources. In the coming years, we see the Centre as a platform for discussing and creating knowledge to support this new thinking by developing novel modelling methods and forms of model integration and multi-criteria indicators for complex infrastructure problems that go beyond boundaries of individual infrastructure systems."

Dr Ana Mijic
Co-Director, January 2021.

The 2030 vision of the Centre is to bring Systems Engineering and Innovation to Civil Infrastructure by changing how cross-sector infrastructure challenges are addressed in an integrated way using principles of systems engineering to maximise resilience, safety and sustainability in an increasingly complex world.

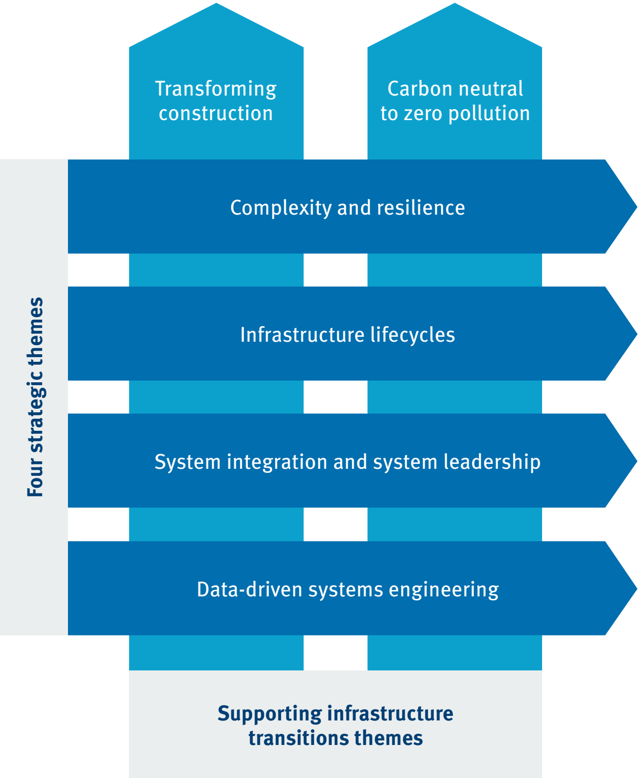
We want to better understand the environmental and societal impacts of infrastructure interventions under uncertainty. This requires a change in current approaches to infrastructure systems engineering: starting from the natural environment and its resources, encompassing societal use of infrastructure and the supporting infrastructure assets and services.

We argue for modelling that brings natural as well as built environments within the system boundaries to better understand infrastructure and to better assess sustainability. We see the work as relevant to both the academic community and to a wide range of industry and policy applications that are working on infrastructure transition pathways towards fair, safe and sustainable society.

This vision was developed through discussions between academics in preparation for the Centre for Systems Engineering and Innovation (CSEI) 10 years celebration. These rich discussions about the future of the Centre were inspired by developing themes for a celebration event, through which we have summarised the first 10 years of the Centre's work and our vision for the future and identified six emerging research areas.

Emerging research areas

The consolidation of previous research and our vision for the future have provided the base to establish six major emerging research areas for work on systems approaches to infrastructure through to 2030.



1. Complexity and resilience

Though difficult to predict, the complexity and the resilience of a system are inherently linked. As we move into an era subject to an exponential growth in complexity and unforeseen systems-wide shocks, understanding how a system operates under stress is a vital part of designing in the resilience that will ensure the stability needed to support continued and considered growth and development.

2. Infrastructure lifecycles

The construction sector is actively adopting strategies to reduce carbon emissions and reduce energy usage across the entire lifecycle of built infrastructure. Research into how the use of materials impacts on design and energy use across the lifecycle of a built asset is key to advancing towards zero-carbon targets.

3. Systems integration and systems leadership

The challenge of improving infrastructure delivery and maintenance across its lifecycle requires a clear understanding of the different elements at play and how they relate and impact on one another. Understanding is the first step, effective leadership to manage that impact is the next.

4. Data-driven systems engineering

Digital technologies both facilitate the effective running of our infrastructure and provide incredible opportunity for improvements in the way we deliver and manage it. How we approach the challenge of leveraging the potential that lies in our use of data-driven systems without being limited by the way it is applied is crucial to optimising its value.

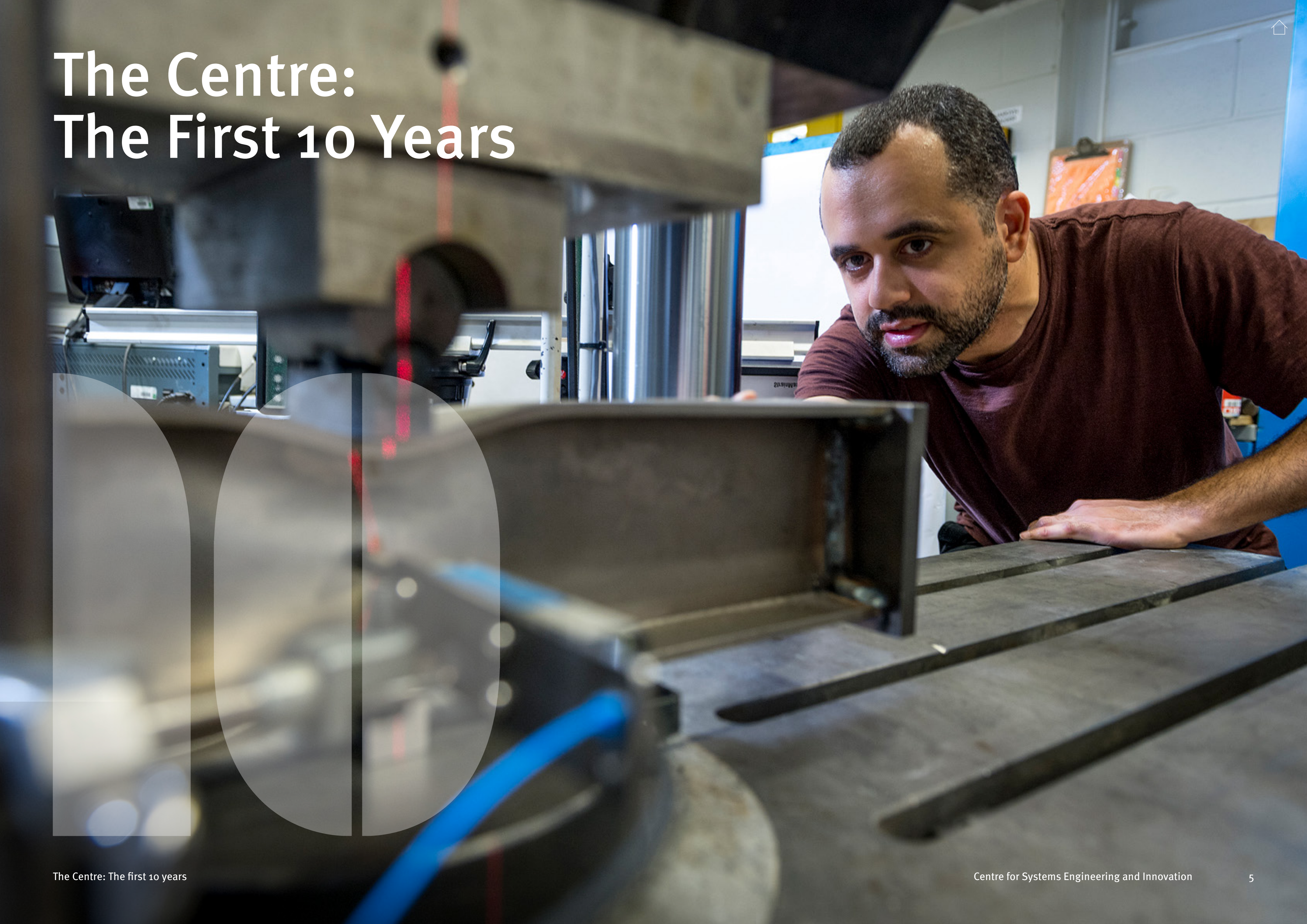
5. Transforming construction: Restart, reset & reinvent

As the construction sector increasingly adopts Design for Manufacturing and Assembly (DfMA), industrialised construction and the use of digital technologies to improve efficiency, sustainability and reduce energy consumption, the risk of leaving SMEs and skilled tradespeople out of the loop is high. As a consequence, this can negatively impact the economy of countries.

6. Carbon neutral to net zero pollution: Built and natural environments

As we enter the new decade, our need to balance economic growth and the development and upgrade of our infrastructure with rapidly changing social and environmental concerns becomes ever more acute. Research into viable routes to reduce pollution, minimise impact on the environment and maintain quality of life explores the question: how can we improve quality of life through infrastructure in a sustainable and fair way, while minimising its impacts on environments?

The Centre: The First 10 Years



The Centre: First 10 years

The Centre for Systems Engineering and Innovation was established in 2010, with the aim of providing a hub for work that brought systems approaches to civil infrastructure.

Over the last decade it has developed related research on complexity, interdependencies between infrastructure systems in water and transport, the potential for projects to act as interventions and a catalyst for change in infrastructure, infrastructure as a system-of-systems, methods supporting the effective integration of systems within infrastructure and associated supply chains, improvements in sustainability through the introduction of blue-green infrastructure, and the challenge of cyber-physical complexity.

Initially, the Laing O'Rourke Centre for Systems Engineering and Innovation, with Professor Fisk as Director, had at its core an MSc programme on Systems Engineering and Innovation, with a focus on building services engineering. From 2015-2020, with Professor Whyte as Director, the Centre expanded its remit on engaged research and Systems engineering leadership with a set of partners and members, including Bentley Systems, EDF, Mott Macdonald, Laing O'Rourke and the Project Production Institute.

The Centre has developed and extended its influence, working with public policy makers, industry bodies and senior thought leaders and executives in industry and government internationally. Professor Fisk is now a member of the UK National Infrastructure Commission.

Heritage — Systems engineering and innovation

Our vision builds on a significant heritage of work on systems engineering and innovation at Imperial College London, and its application to the complex challenges of infrastructure. Programmes of research started in the Department of Civil and Environmental Engineering as early as the 1900s, seeking to model the impact of change on construction management, water resources, risk and computer applications and modelling.

Over more than 20 years, as the complexity of civil engineering projects increased, facilitated by new developments in physical and digital technologies, the broader systems-wide impact of changes to the built environment and civil infrastructure became ever more apparent.

This seeded increasing interest in large, systems scale challenges, a broader exploration into water resources management, urban regeneration, asset management and infrastructure integrity, international development, climate change and energy use, the construction process which then developed into research into the infrastructure lifecycle, risk/safety/health, waste minimisation and resource management, and sustainable development.

Research themes in the first 10 years

As a research-led Centre, our work has connected with government and industry strategy on digital, manufacturing and performance as areas for improvement, contributing through three main research themes: 1) production systems, 2) infrastructure interdependencies, and 3) lifecycle.

Through this work, projects have been seen as interventions into infrastructure systems, and interdependencies across infrastructure sectors, such as transport, water, energy and buildings, are important to a smart and sustainable built environment.

We have played a major role in the government agenda around Transforming Construction, with Professor Whyte sitting on the main board of the Construction Leadership Council.

Above
Ray O'Rourke, Laing O'Rourke and Rector Keith O'Nions, Imperial College London (2010)

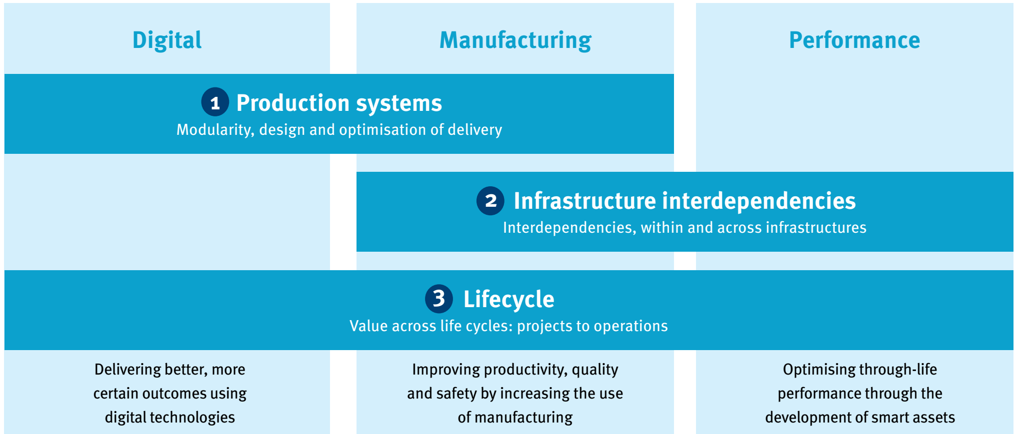
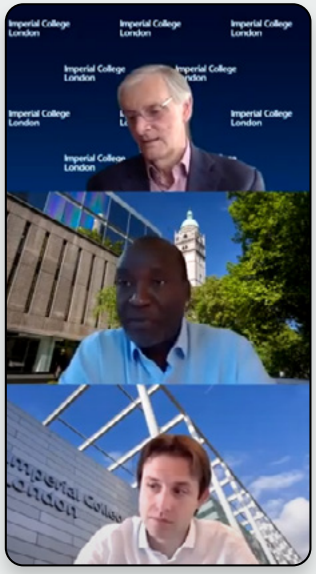


Figure
Our 2015-2020 research themes addressing sector challenges around transforming construction

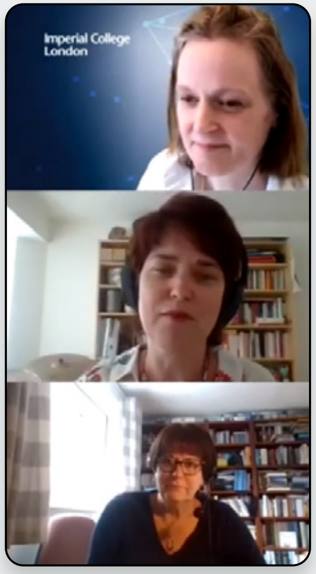
The Centre: First 10 years

Celebrating 10 year of systems engineering and innovation, 7th July 2020

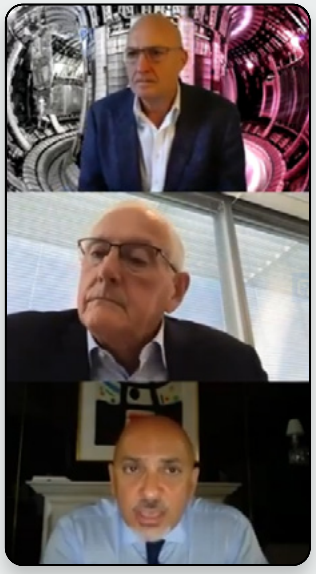
From top to bottom
Dr Ana Mijic (Co-Director), Dr Marc Stettler and Dr Mike Cook discuss new ways to consider infrastructure as part of the natural environment to support a move towards zero pollution.



From top to bottom
Professor David Fisk (Founding Director), Professor Washington Ochieng (Executive Director), and Dr Panagiotis Angeloudis, discuss complexity and resilience.



From top to bottom
Professor Jennifer Whyte (Co-Director) talks to Dame Judith Hackitt and Professor Mary Ryan who closed the event with remarks on the need for interdisciplinary and systems ways of working.



From top to bottom
Professor David Gann talks to Ray O'Rourke CEO of Laing O'Rourke, and the Minister for Construction, Nadhim Zahawi, who expresses great interest in systems engineering and the work of the Centre.

Overview

The celebration event gathered over 200 leading Government, academic and senior industry figures to celebrate our decade-long achievements. At this celebration, speakers expressed the appetite for systems engineering to further address global infrastructure challenges.

The event was delivered virtually, and was organised around discussions on how the Centre informs current debate around systems approaches to infrastructure and how we plan to shape the research agenda and industry practice through to 2030.

Watch on YouTube

Nadhim Zahawi, Minister for construction
Keynote at our 10 year celebration event, expressing great interest in systems engineering and the work of the Centre.

7 July 2020

"The Centre is I think an example of what Imperial College does best. A combination of deep understanding of relevant technology, but a wider appreciation of its role and function within society and how it can best be used."

Dame Judith Hackitt
Drew on her work on building safely, emphasizing the need for putting "people into systems engineering"

7 July 2020

"It really is great, I think, to see this greater awareness that is building around systems engineering and systems thinking… [because] some of the tools we use and that traditional systems engineering use are struggling to cope with the complexity of the challenges that we now face."

Dr Mike Cook
Buro Happold chaired a session that discussed approaches to net-zero pollution.

7 July 2020

"We must move towards considering the natural ecosystem and services we rely on from natural environment for future generations in built environment infrastructure decision-making."

Professor Mary Ryan
Closing the event by emphasising the need for putting people into systems engineering and collaborative working.

7 July 2020

"We should be thinking more holistically about the environment and how engineering impacts the environment, [systems engineering] is a way to go beyond thinking in silos because silo thinking leads to unintended consequences."

"The importance of systems engineering, and the benefits of systems approaches, are going to be critical."

Nadhim Zahawi,
Minister for construction

Emerging research areas

Complexity and resilience

Authors
Professor David Fisk, Dr Panagiotis Angeloudis,
Professor Washington Ochieng

Image
The View from The Shard,
London, United Kingdom

What is the problem?

In a conventional approach to building a system, the whole design is tested only when construction is complete. This approach works for simple projects but becomes unreliable as the system complexity increases.

The tried and tested systems engineering solution breaks the design task down into layers of ever smaller blocks until they correspond to identifiable components. The design is then realised by assembling the layers of blocks, testing realised performance against the design at each level of assembly. However, as the complexity of the design increases further, even this approach incurs problems. Controlling growing complexity is the issue.

How does our research address this?

Complexity has no intrinsic value, but it is an inevitable consequence of a large multi-function product. Although complexity is a common experience, research has brought some much-needed clarity into what it might mean. Although each engineering discipline may feel it has its own complexity problems, research can draw on a wide field to make more general insights.

Disciplines such as ecology, computer science and statistical physics have provided insights into how engineering complexity can be better understood. It has also been possible to look at the large data sets that are now available for real world complex system dynamics.

What have we achieved so far?

In computer theory, the Kolmogorov complexity of an entity is the shortest full description that retains all its detail. So, whereas the description of a straight tunnel might simply be the same few meters repeated, the description of a new hospital of similar cost would have much less to simplify. In an argument originally made in ecology, it is the size of the complex core of the compressed description that hints at whether the system could become unstable. The larger the complex core the more chance it has to find an unstable pathway.

This argument has helped our understanding of how the system dynamics will change as more system components are added. For example, analysis of data from the world's metro systems showed that they tended to avoid adding to stations with high levels of line connectivity for practical reasons, but as a consequence their flows would be more stable and more robust against attack.

In contrast adding more flights to a hub risks disrupting a global system that could be unstable to interruptions. Now digital complexity adds a new dimension and research challenge.

What are the future directions for research and industry?

Data techniques such as building information models and digital twins promise to improve infrastructure design and assembly for complex projects.

However, digital technology presents a whole new world of complexity, because a program has an infinite number of possibilities. The only way to be sure that a program will have the properties required is to run it.

As a consequence, the classical systems engineering approach of breaking down a system into subsystems is not guaranteed to provide assurance that the final stages will work when brought back together. The response has been to adopt an approach that is sometimes called 'agile'. The most essential required outputs are programmed first.

The next most essential are then added and tinkered with until they too work. In some engineering applications this approach may not be feasible, and the software simply has to be tested exhaustively. As this can take time, leaving writing software until the last stage of a project may be a disaster.

Research is needed to ensure that projects benefit from the flexibility of data-driven systems without crashing into complexity failure.

What is the long term vision for impact?

A society that hopes to remain sustainable needs to master how it will contain the threat of increasing complexity. The ability to collect, share and analyse data should give much better performance from future systems. This should include their resilience to shocks. However, without research on how this can be delivered, it is only a matter of time before complexity overwhelms us all.

Related researchers

Dr Panagiotis Angeloudis
Reader in Transport Systems and Logistics

Professor David Fisk, FREng
Emeritus Chair in Systems Engineering and Innovation

Professor Washington Ochieng FREng
Chair in Positioning and Navigation Systems

Dr Michel-Alexandre Cardin
Senior Lecturer in Computational Aided Engineering

More information
https://imperial.ac.uk/systems-engineering-innovation/complexity-and-resilience

Emerging research areas

Systems integration and systems engineering leadership

Author
Professor Jennifer Whyte

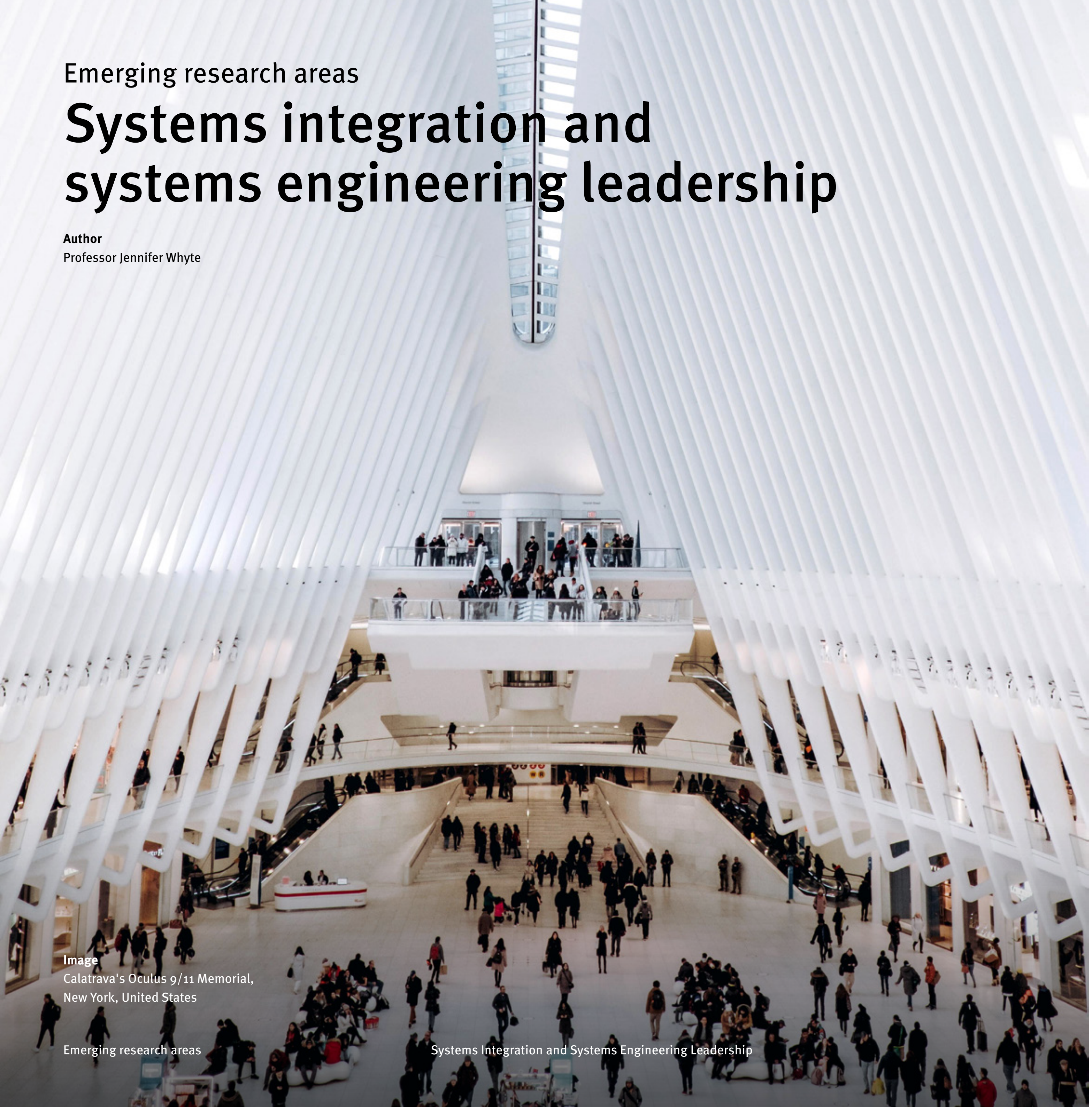


Image
Calatrava's Oculus 9/11 Memorial, New York, United States

What is the problem?

Infrastructure systems are interdependent open systems of systems. Approaches to project delivery that focus only on the management of contracts have not been effective, leading to delays and cost over-runs in delivery, but also not delivering the best outcomes for society.

As projects are interventions into existing infrastructure systems of systems, their construction and maintenance involve many different types of engineering knowledge. There are many forms of complexity and uncertainty spanning the technological, ecological, and socio-political, both within and across project boundaries.

How does our research address this?

We have been championing an approach to projects as interventions into infrastructure, with a focus on the systems that the project delivers. Within the project, the focus is on how the architecture is partitioned into sub-assemblies and components, and then these, and the interfaces between them, are tested (both verified, to ensure they meet regulations, specifications and requirements; and validated, to ensure they meet stakeholder needs). Across project boundaries, the focus is on the engagement with stakeholders and the intended and unintended technological, environmental and social impacts. This requires rethinking standard systems engineering approaches, while retaining the focus on verification and validation of designs at every stage.

For the delivery of complex infrastructure products, the focus is on the intervention, conceived and handed over in relation to existing infrastructure, and tested at different levels, from component, to sub-system to system in delivery, supporting the concept of adaptability and flexibility of infrastructure systems.

What have we achieved so far?

This work on systems integration has been foundational for the work of the Centre over the last 5 years and has informed government and industry policy in the areas of production systems, infrastructure interdependencies and lifecycles. We have identified the importance of interfaces and buffers between levels (within and across project boundaries), distribution of related responsibilities, and evolution over time. We have trained managers in systems engineering leadership; written research papers on projects as interventions; and articulated how project managers need greater focus on the system they are delivering, rather than managing contractual arrangements.

This work has informed contributions to the post Hackitt review work on Building Safely, and also the government Transforming Construction initiative. We have also worked with the Sheffield City and Derby, Derbyshire, Nottingham, Nottinghamshire Local Enterprise Partnerships to inform small and medium sized enterprises about how they might engage with modern methods of delivery and supply chain integration.

What are the future directions for research and industry?

Systems Approaches to Infrastructure are becoming widely recognised as important, with work by the Institution of Civil Engineers, Royal Academy of Engineering and others and work on outcomes-based approaches to procurement. There are particular needs for better metrics and for indicators for projects, and for new approaches to modelling complexity and uncertainty within and across project boundaries.

What is the long-term vision for impact?

The long-term vision is to develop new methods for delivering projects as interventions into infrastructure systems of systems, with richer information on use, and on environmental systems as well as financial returns.

Related researchers

Professor Jennifer Whyte
Centre Co-Director, Laing O'Rourke / Royal Academy of Engineering Chair in Systems Integration

Dr Luigi Mosca
Research Associate

Dr Kate Simpson
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Dr Ranjith Soman
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Alexander Zhou
Research Postgraduate

Hongmin Zhu
Research Postgraduate

More Information

Royal Academy of Engineering and Laing O'Rourke Chair in Systems Integration https://www.imperial.ac.uk/systems-engineering-innovation/research/Research-Chair/

Research on Supply-Chain Integration and Regional Innovation

https://www.imperial.ac.uk/systems-engineering-innovation/research/raeng-regional/

Data-Centric Engineering - Alan Turing Institute / Lloyds Register Foundation https://www.turing.ac.uk/research/research-programmes/data-centric-engineering/data-centric-engineering-challenges

Emerging research areas

Data-driven systems engineering

Authors
Professor Julie McCann, Dr Ivan Stoianov

Image
Imperial College London's Data Science Institutes Data Observatory

What is the problem?

Climate change, the Covid-19 pandemic and the urgent need for a sustainable co-existence between humans and the environment is likely to accelerate the digital transformation for complex critical infrastructures such as water, food, transport and electricity.

The resilience and sustainability of these complex infrastructures rely upon the acquisition and analysis of data with unprecedented spatial and temporal resolution, the application of advanced modelling, optimisation and control methods, and the integration of multiple disciplines and expertise to develop solutions.

Recent advances in data analytics are impacting the way we engineer systems, creating unique challenges and unmatched opportunities, advancing theory, methods, tools and practice of data-driven design. Data, typically from networks of distributed sensors and actuators, can help enhance designs, optimise performance, provide timely warnings of failures, support automation and make better use of resources. Yet current SCADA (Supervisory Control and Data Acquisition), IoT (Internet of Things) and IT systems, key to the timely, reliable and secure delivery and access to data, are not designed with the rigour, reliability and agility to meet the needs of multiple applications and users in order to maximise investment returns. This gap brings many research challenges, the most important of which is the co-design of both the computing (SCADA/IoT/IT) and engineering infrastructures.

How does our research address this?

Our research explores the gap between engineering infrastructures and computer systems engineering and, in doing so, focuses on the notion of cyber-physical interaction. Take the next generation water networks, which dynamically adapt their connectivity and hydraulic conditions in order to improve resilience, minimise leakage, reduce energy use and carbon emissions, and respond to incidents such as pipe breaks (e.g. change network connectivity to avoid interruptions to supply).

The design and control of such dynamically adaptive water supply networks led to the development of novel monitoring and control technologies, and their integration with advances in hydraulic modelling and mathematical optimisation. Currently, the main challenge is the near real time and large-scale implementation of the developed technologies and methods in complex operational systems.

For example, how can we guarantee the reliable, secure, accurate and timely provision of large volumes of data, and also the actuation of control valves, from a distributed system in near real-time via unreliable radio networks, and battery-operated sensor and actuation systems, which operate in a rather hostile environment (e.g., frequently flooded underground manholes)?

What have we achieved so far?

Through several projects (e.g., the NEC Smart Water network project), we have developed monitoring and control technologies, hydraulic modelling and mathematical optimisation methods for the design and operation of dynamically adaptive networks. We have implemented these methods in five water distribution networks in England.

We have been working on the scalability of this approach to deliver unparalleled controllability and observability of water supply networks in order to improve their resilience and address multiple operational objectives. Our methods and technologies have also been deployed during the Covid-19 pandemic to ensure the resilient supply of water to critical customers (e.g. the Nightingale hospital in Bristol).

A key task to address the scalability challenge is the reliable, secure and timely acquisition of data. We were the first to build a low-powered wide-area radio communications protocol that can provide the guarantees required to support slow-feedback control of systems (e.g. water supply networks).

In addition to the management of water supply networks, and as part of the Lloyds Register Foundation/Alan Turing Institute “Data Centric Engineering” Programme, we are examining how decentralised near-shot machine learning can drive wireless actuators to support rainwater collection in Singapore and how sensor systems can provide early yield detection for precision farming in English Vineyards.

Working with the PeTraS IoT Hub and the Tate, we are building security protocols for real-time logistics. Our Industry 4.0 work designs sensor systems that carry out on-board machine learning for factory automation optimisation, asset management and predictive maintenance via RF Shadowing. Indeed, our RF Shadowing work is allowing us to reuse the communications radio as a sensor, sensing things like rotational machines, water content of grapes or indeed liquid changes in human lungs.

Returning to cyber-physical interaction, our EPSRC programme grant, S4 Science for Sensor System Software, has been exploring tools and methodologies, such as verification, formal analysis, to provide systems engineers with guaranteed reliable or correct systems.

Future directions and long-term vision for impact

Our ultimate ambition is that through the understanding of cyber-physical interaction, systems engineering design will automatically involve the co-design of the computer and physical systems in tandem in highly challenging complex engineering and commercial contexts.

The long-term vision is that such approaches, tools and methodologies will produce technologies and systems that can solve the large societal issues - the greater resilience and sustainability of infrastructures such as transport, food production, water and energy provision. Key to this are the novel computational aided engineering methods developed to support the systems design process. One example is the work on a decision rule approach to *Flexibility in Design* (also known as *Real Options*), studied as a concrete enabler of sustainability and resilience in complex systems.

Flexibility promotes sustainability by recognizing the ability to change and make better use of limited resources (e.g., expanding capacity *if and when* needed). It also enables better resilience by allowing a system to adapt and reconfigure after unexpected shocks or disruptions. It helps the system regain (or even surpass) pre-disruption conditions and performance, supporting the concept of antifragility. Such analysis stretches current computational methods and must rely on new digital processes, stochastic optimisation, and machine learning algorithms to better support design and decision-making activities, in such a deeply uncertain, and heavily data-driven environment.

Technological novelty can provide levels of secure autonomy for infrastructure only if we have the science to better understand how the technology behaves and be able to provide guarantees.

Related researchers

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Dr Panagiotis Angeloudis
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Senior Lecturer in Computational Aided Engineering

More information

Infrasense Labs http://www.infrasense.net/

Data-Centric Engineering - Alan Turing Institute / Lloyds Register Foundation https://www.turing.ac.uk/research/research-programmes/data-centric-engineering/data-centric-engineering-challenges

Example project on enhancing critical ecosystems https://www.turing.ac.uk/research/research-projects/enhancing-critical-ecosystems

Example project on using data science in retrofit https://www.turing.ac.uk/research/research-projects/retrofit-design-built-environment

Transforming construction: Restart, reset & reinvent

Authors
Professor Jennifer Whyte, Dr Luigi Mosca

Image
Scale Space mapping
White City Campus

What is the problem?

If the key to transforming the construction sector lies with a move towards increased use of digital engineering capabilities, DfMA and offsite manufacturing, then there is a risk that a significant proportion of the supply chain will be left behind. The UK government has stressed the importance of ensuring the SME supply chain stays connected with changes in the sector in a variety of guidance documents and by investing in funded programmes, one of which is the Transforming Construction Network Plus (N+) programme.

How does our research address this?

The research team at the Centre for Systems Engineering and Innovation recognised the potential for adding significant value to the N+ programme. Working with the Warwick Manufacturing Group (WMG) at the University of Warwick and University College London (UCL) a collaborative proposal was submitted to Innovate UK.

The successful bid has provided our research team with an excellent opportunity to extend existing research into ways in which DfMA, digital technologies and the development and introduction of new business models can be used to deliver value to infrastructure clients and actively support SME engagement and skills development as part of the process.

Research spans both the national and regional level by mapping the systems integration activities of SMEs across regional supply chains. This approach is providing us with the opportunity to explore the critical success factors in strategic alliances between large and small and medium-sized enterprises (SMEs) in the construction industry. These alliances will support the adoption of new technology across the supply chain.

What have we achieved so far?

The project builds on research undertaken and published through grants from the Royal Academy of Engineering on 'Regional innovation systems and the transformation of construction into a manufacturing process' and through the Transforming Construction Network Plus.

With a view to sparking interest and discussion across the sector, the team have distilled findings from their research into two easily accessible Transforming Construction Network Plus digests: *Changing Business Models — Implications for Construction, and Platform Thinking for Construction*. The digests provide a clear and easy way to understand the relevant considerations for companies of all sizes, as well as providing the basis for considering how and why business model change and the adoption of platform technology hold the key to wide-scale improvements in the construction sector.

The research team are collaborating with leading construction, engineering and software companies, and have hosted international webinars to explore how new business models for modern methods of construction are emerging throughout the world and how they are relevant to creating the 'tipping point' in the sector envisioned in the UK Transforming Construction Agenda.

What are the future directions for research and industry?

The overall aim of our work on Transforming Construction is to bring together research academics, industry and policy representatives and thus establish and develop a new community and body of knowledge to guide the sector through the transformational change needed in the coming years.

A key element to this is ensuring all parts of the supply chain are engaged. Our involvement has established a foundational position that can be developed by engaging with both regional and national policy makers to understand how to collaboratively develop new business models and review, assess and integrate suitable platform approaches to support increased transition to offsite construction.

What is the long-term vision for impact?

We face major challenges in the coming years. Climate change is driving urgent policy and regulatory change by governments internationally to reduce emissions and transition towards zero carbon and zero pollution.

The construction sector has proven that offsite manufacturing offers significant reductions in carbon emission and energy usage whilst at the same time reducing project delivery times and accident frequency rate. However, construction supply chains consist of a multitude of smaller businesses and skilled trade people that at present have no connection or involvement with these new approaches. Our research offers an important element to ensure that we can collectively address this problem and support a transition to a robust, secure and inclusive construction sector.

Related researchers

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Research Associate

Professor Jennifer Whyte
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Research Postgraduate

More information
https://www.imperial.ac.uk/systems-engineering-innovation/Restart-reset-and-reinvent/

Emerging research areas

Infrastructure lifecycles

Author
Dr Rupert J. Myers

Image
London Overground

What is the problem?

Infrastructure systems are essential to society and underpin the nature of the built environment (spatial distribution, type, etc.), since they provide numerous basic services such as: transport (road, rail, etc.); energy (electricity distribution and transformation, etc.); water (sewage, water treatment, etc.). Their high social importance, and characteristically long lifetimes and high initial investments, are key reasons why infrastructure systems are usually both constructed and operated by an organisation. For example, the London Underground, initially constructed and operated by the Metropolitan Railway in the mid-1800s, is currently operated by Transport for London.

These key aspects distinguish the ‘product’ lifecycles of an infrastructure system, i.e., including construction, use, and end-of-life stages, as ‘service-oriented’ rather than ‘production-oriented’, whereas the latter is common to most other products, such as clothing and fast-moving consumer goods. Therefore, infrastructure systems already embody the core ‘service-oriented’ element of the circular economy.

The key for a sustainable infrastructure system is thus to reliably deliver its social service(s) without excess cost(s) (to the managing organisation and society) and environmental impacts.

How does our research address this?

Opportunities to improve infrastructure systems exist along their whole lifecycles. During use, regular field sampling and measurement of durability indicators should be implemented to predictively spotlight material degradation, enabling smaller targeted maintenance rather than larger and more costly repairs. Data-driven approaches and sensor technology will be key here, and provenance of infrastructure materials in databases will be built up. These data will underpin a good understanding of the quantity and quality of this 'material bank', which should be leveraged at end-of-life to facilitate reuse and recycling, with the infrastructure manager taking on the role of a material supplier.

What have we achieved so far?

The potential of reuse and recycling to reduce environmental impacts should be balanced with component and build complexity, e.g., modular/upgradable/replicable vs. in-situ/unique construction, since simpler materials and components are more readily recycled, and facilitate reduced construction complexity.

This balance should also account for environmental benefits that may be achieved through use of multi-functional materials and components, e.g., permeable concrete paving. Therefore, infrastructure systems should preferably employ simple and multi-functional materials and components, which in turn must be facilitated through good materials selection and design.

During the early stages in the design process, functional subsystems should be systematically developed to meet the social need(s)/service(s) of the whole infrastructure system, and complementarily/concurrently scenarios of their embodiments should be screened using lifecycle assessments at this same (whole system) level. This use of lifecycle assessment to authentically indicate environmental performance of the infrastructure system, that is to say of the (physical) 'product' lifecycle rather than the (conceptual) 'project' lifecycle, must be driven by the infrastructure owner-operator and facilitated by other key stakeholders (e.g., capital investors), and go beyond check-box type certifications: a sustainable infrastructure system must reliably provide its service(s) and meet both the specified product-based and project-based lifecycle economic and environmental performance criteria. Ultimately, this assessment must demonstrate benefits to the owner-operator, material suppliers, designer, investors, and other key stakeholders along the infrastructure life cycle.

What are the future directions for research and industry?

Industry needs to work towards comprehensive assessments of environmental pressures along the entire life cycles of infrastructure systems, so not only the initial production and construction stages, but also including use and end-of-life, as well as both direct and indirect environmental pressures (e.g. emissions).

Research is needed to simplify the practical application of life cycle assessment to infrastructure systems, and to identify new products or systems with improved environmental performance and to support their development.

The overarching future direction is working towards providing more reliable infrastructure services at higher resource efficiency.

What is the long-term vision for impact?

Availability of reliable methods and databases to assess environmental performance of infrastructure systems that can also be readily understood and applied, e.g. within a responsive/digital framework such as the digital twin, and a fluid pipeline of innovation from materials/systems discovery to industry application (including uptake in the aforementioned databases).

Related researchers

Dr Rupert J. Myers
Lecturer in Sustainable Materials Engineering

Dr Arnab Majumdar
Reader in Transport Risk Management

Professor Chris Cheeseman
Professor of Materials Resources Engineering

More information

https://www.nature.com/articles/s41467-020-17583-w - CO_2 uptake in cementitious materials overtheir lifetimes

https://pubs.acs.org/doi/10.1021/acs.est.9b05550 - life cycle environmental impacts of alternative cements

RICE project focuses on component-level substitution and associated changes in environmental impacts

Assessing Material Efficiency in Buildings (https://gtr.ukri.org/projects?ref=EP%2FS006079%2F2#/tabOverview), which focusses on building-level substitutions.

SysTeM project – policy analysis of component-level substitutions in buildings (https://www.imperial.ac.uk/systems-engineering-innovation/research/2020-small-call-winners/), to translate the research findings into policy recommendations

Emerging Research Areas

Carbon neutral to net zero pollution: Built and natural environments

Authors
Dr Ana Mijic, Dr Marc Stettler,
Dr Rupert J. Myers

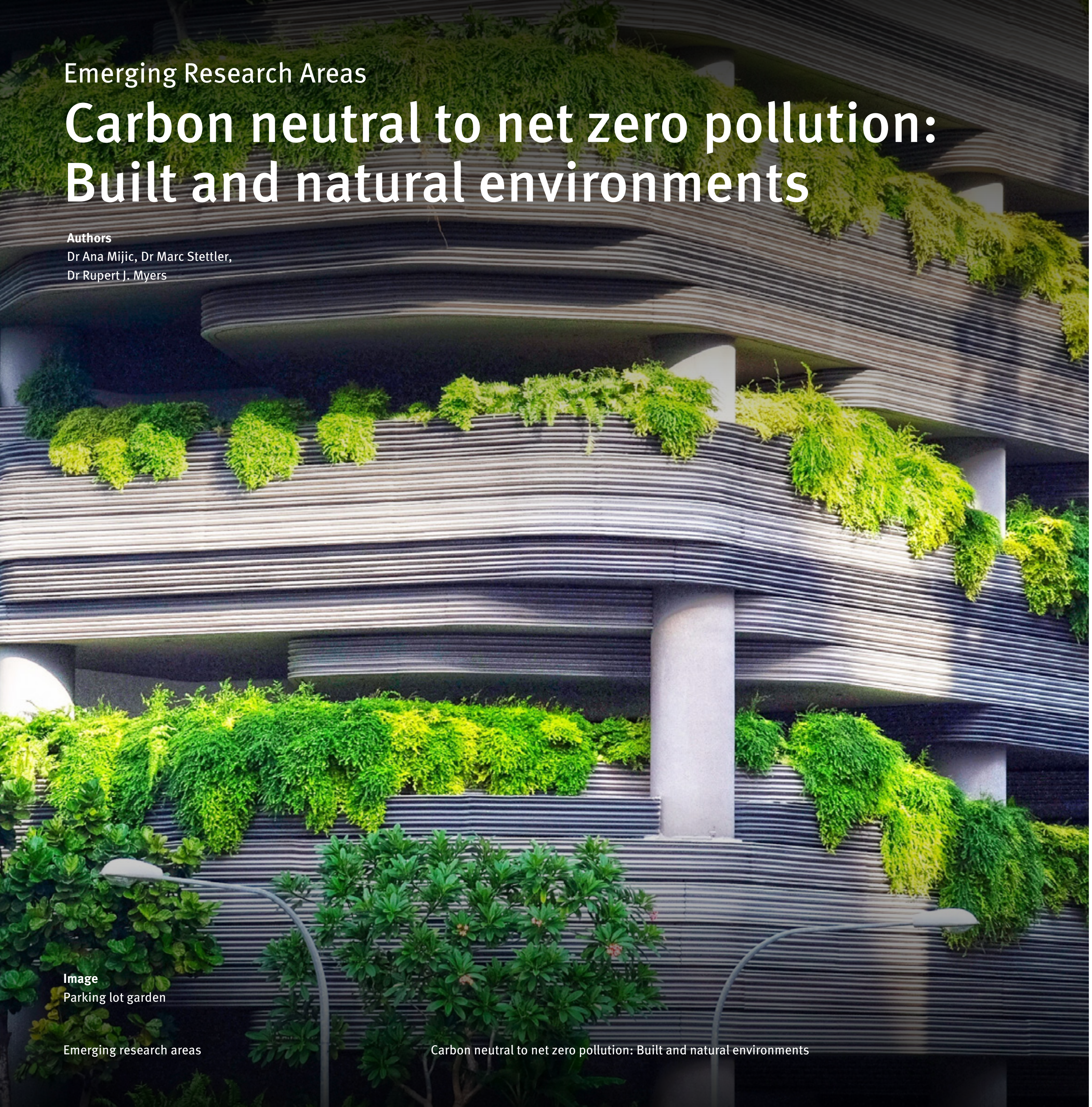


Image
Parking lot garden

What is the problem?

Infrastructure is vital to society and provides us with energy, water, transport, telecommunications, and waste management. For most of human development, infrastructure has been seen as separate from environment. However, as the scope of human activities has changed creating significant environmental impacts, the role of infrastructure has transitioned from supporting human systems to also managing the natural environment.

This raises a question of addressing systemic impacts of infrastructure projects and the role of civil and environmental engineering in creating and maintaining the built environment.

Global focus is currently on reducing greenhouse gas (GHG) emissions through setting the Net Zero Carbon Zero targets at national levels and science-based targets for companies[1]. This is of course beneficial to tackling global climate change. However, systemic impacts that refer to both direct and indirect long-term impacts extend beyond the carbon footprint and spatial boundaries of an infrastructure project.

These impacts, which cause the environmental damage — including biodiversity loss, and severe air, water, and soil pollution — are due, at least in part, to direct environmental pollution[2] in some form or another. In addition, indirect environmental impacts due to infrastructure in the form of embodied pollution associated with infrastructure materials, together with water and land footprints pose additional strain on the natural environment and affect its ecosystem services. The data portrait devastating impacts of pollution at a global scale, with annual number of cases of premature death linked to the use of natural resource and environmental damage currently reaching 19 million.

Our infrastructure decisions contribute to the pollution that our society generates; however, they can also determine how we manage the trends of population growth, urbanisation, and growing consumption. Within that context, infrastructure is critical in shaping the set of viable routes to reducing environmental pollution in the future.

We argue that civil and environmental engineers must pay a crucial role in creating solutions that will promote sustainable development. This raises the question: how can we continue to improve quality of life through infrastructure provision, while minimising our impacts of pollution on the natural environment in the world that we have already created?

How does our research address this?

Our understanding of pollution impact pathways continues to evolve and improve, and while we understand some pathways quite well (e.g. the toxicity of leaded fuels), new forms of pollution continue to emerge, such as microplastics and nanomaterials, which pollute our air, water and soil.

A more challenging aspect of the impact pathways assessment is the feedback between the environmental damage, which alters ecosystems and consequently impacts both humans and non-humans, and the structure of built environment. Concepts such as the natural capital have been developed to assess the value of ecosystem services provision for people. Nonetheless, the link between the direct and indirect impacts assessment, as well as the implications for non-humans, is still a scientific and practical challenge.

The need for holistic assessment is justified by four key aspects of the sustainable development debate. Firstly, focusing on a single issue could potentially result in a range of unintended consequences that are already known, or yet to emerge ('burden shifting'); for example the growth in the diesel cars market in the UK in the early 2000s, partly driven by lower taxes to reward their lower carbon dioxide emissions, degraded air quality in cities.

Secondly, focussing on a single form of pollution could miss synergistic opportunities for regenerative solutions: for example, there are often co-benefits of reducing carbon emissions and improving flood management and other ecosystem services that strengthen the case for change. Thirdly, when discussing the future of infrastructure systems we need to recognise their importance not only in the context of industry, innovation, and affordable and clean energy, but also for achieving other aspects of sustainable development, as embodied in multiple Sustainable Development Goals such as clean water and sanitation, sustainable cities and responsible consumption.

Finally, reframing the debate in the context of a systems-level pollution expands the 'burden of proof' from regulators to include those causing or facilitating pollution, which is important for forms of pollution whose impact pathway is not well understood[3].

[1] For example, using science based targets: https://sciencebasedtargets.org/

[2] In this article, we define direct pollution to be the addition/change in quantity of any substance (solid, liquid, or gas) or any form of energy (such as heat, sound, or radioactivity) to the environment at a rate faster than it can be dispersed, diluted, decomposed, recycled, or stored in some harmless form. Sources of pollution are extremely diverse, and the specific harm caused by different pollutants depends on the environment in which they is released.

[3] It has been argued that the precautionary principle shifts the burden of proof onto the proponent of an activity, i.e. the proponent of an activity must show any resulting pollution does not cause harm [25].

What have we achieved so far?

Systems-level pollution thinking will require fundamental revaluation of our infrastructure systems that necessitates inter-disciplinary research, innovation, and collaboration. Expanding the scope of analysis beyond approaches narrowly dealing with single environmental issues or pollutants, e.g., carbon accounting, has already revealed opportunities for thinking differently about infrastructure operations and planning. Analysis in the aviation sector has shown that minor changes to the altitude at which aircrafts fly could significantly reduce the climate impact of flying attributable to contrails without significantly increasing CO_2 emissions.

The most effective way of achieving environmentally- and pedestrian- friendly urban design is to integrate transport infrastructure and public space planning, in addition to reducing pollution. Systems modelling of the urban water-energy nexus enabled us to analyse impacts of carbon policies on water infrastructure planning, while the water abstraction operational rules discovered through integrated modelling of urban water infrastructure have shown a potential to provide infrastructure equivalent benefits of up to £200 million.

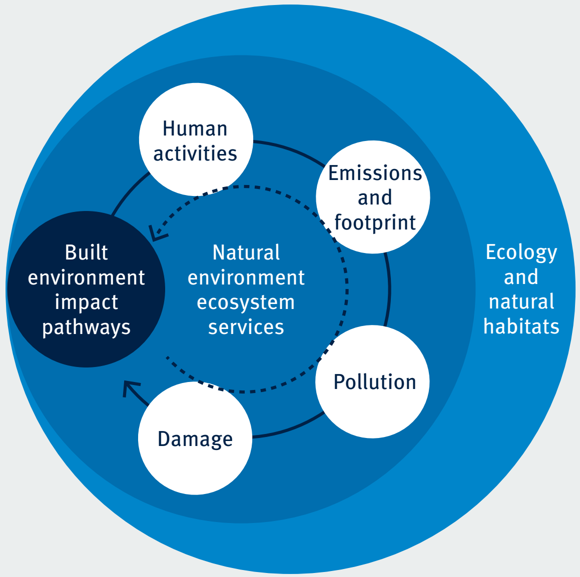
Finally, lifecycle assessment has emphasised the role that materials can play in reducing environmental impacts of infrastructure systems, such as using alternative cement binders with lower CO_2 emissions relative to conventional blended Portland cement binder.

What are the future directions for research and industry?

Examples across multiple infrastructure sectors provide a new conceptualisation of a system that is designed to support both built and natural environments. Understanding of pollution impact pathways resulting from human activities — and importantly environmental damage — is crucial for assessing the overall sustainability of the complex anthropogenic Earth system.

We refer to this concept as a net zero pollution (NZP), which aims to achieve a systems-level balance between human footprint and the capacity of natural system to support life on Earth. This concept supports the debate about development within planetary boundaries, which needs to be revisited considering the role of built environment in managing natural systems[Fig.1].

Figure 1
Net zero pollution concept in the context of built and natural environment, which promotes balancing built environmental impacts with the capacity of the natural system to support life for all its inhabitants



For direct pollution, the concept implies either elimination of all pollution sources to the natural environment (zero pollution), or in case the pollution is released into environment, its removal to minimise damage, which could be in a different place or at a different time (net zero pollution). This principle works well in the context of managing GHG emissions through Net Zero Carbon accounting. It could also work in some cases where habitats are destroyed and rebuilt somewhere else, which is promoted by the biodiversity net gain approach. However, the net zero pollution concept may be particularly challenging for the forms of pollution or cases when the damages are non-linear and spatially dependent.

Such examples include impacts of agricultural diffuse pollution on river water quality, which needs to be removed at some point downstream for a water treatment, with potential significant damage in between the source of pollution and the abstraction location. In the context of air pollution, local impacts on health due to GHG emissions cannot be mitigated if pollutants can be taken out of the air somewhere else. Finally, the destruction of unique, old habitats due to the development and resources extractions may be impossible to replicate.

Seeing the coupled human-natural system through the NZP lens poses multiple challenges with respect to understanding and quantifying the complexity of interactions across system components. It increases the importance of, and the need for, data and models to describe both infrastructure systems at the engineering level, and the infrastructure system-of-systems at the societal level, including:

- Modelling interdependences between physical (built and natural environment) and socio-economic (human activities) systems. Here, approaches such as system dynamics, surrogate and agent-based modelling may prove to be invaluable.
- Assessing feedbacks between environmental impacts, damage and state of the natural environment. This could be done by applying industrial ecology methods such life cycle assessment, material flow analysis, and footprint analyses, which could play a significant role in evaluation the systems-level sustainability indicators.
- Interdisciplinary expertise required to effectively develop and use these data and models to perform the more systematic analysis. This will be particularly important in the context of informing important societal decisions.

What is the long-term vision for impact?

The natural world is in crisis and a different perspective is needed — transitioning to net zero pollution enhances focus on the natural environment from a systems perspective, with a potential to facilitate better planning and decision making, and hopefully also environmental protection for the sake of future generations. In order to achieve that, we all need to change the way we think about infrastructure systems and see them as enablers of the transition to zero pollution rather than acting as a barrier to sustainable development.

Related researchers

Dr Ana Mijic
Centre Co-Director and Senior Lecturer in Water Systems Integration

Dr Marc Stettler
Senior Lecturer in Transport and the Environment

Dr Rupert J. Myers
Lecturer in Sustainable Materials Engineering

Dr Michel-Alexandre Cardin
Senior Lecturer in Computational Aided Engineering

More information

Example project on water infrastructure-environment interactions with the focus on London:
https://www.camelliawater.org

Example online tool for appraisal of synergies and trade-offs of feasible decarbonisation pathways on the national scale of Europe:
https://www.european-calculator.eu

Benefits and outcomes

Our research has led to benefits for our industry collaborators, as well as for other research stakeholders, such as policy-makers and professional institutions. It has also increased the level of expertise in the sector, through training and education, providing long-term benefits to our members and partners, and to the sector as a whole.

Benefits and outcomes

Laing O’Rourke: A 10-year celebration of collaboration and innovation

Image
Grange University Hospital, Cymbran Wales, an example of full DfMA

Systems Engineering — fundamental to delivering our most complex projects

The pioneering application of Systems Engineering, on projects such as Heathrow’s Terminal 5, is just one example of Laing O’Rourke (LOR) embracing best practice principles and innovation, throughout our ten-year relationship with Imperial College London.

What began as Design for Manufacture and Assembly (DfMA 70:60:30), has continued to develop our Modern Methods of Construction (MMC) approach and delivery model.

This has been built on for over a decade, delivering against two key objectives:

- Continual investment in a specialist engineering function
- Development and improvement of a leading-edge engineering skills base, through the sponsorship of PhD students, funded research and skills training.

Continued focus on R&D to transform the construction industry

By continuing to focus on research and development, Laing O’Rourke’s approach always starts with an objective look at the business requirements of a project or technology opportunity. Only then can the key objectives and outcomes be developed, followed by the technical detail that is required. This ensures systematic project delivery that meets requirements and delivers quality commercial outcomes.

Top
Leadership CPD at Imperial

Right
Crossrail Train

Laing O'Rourke develops new business models to transform construction, with digital systems integration now fully part of their DNA. A commitment to MMC encompasses both digital and technological innovation, and this runs directly in parallel to the practical advice given to project leaders, to ensure continuity and consistency between project set-up and the subsequent operational delivery.

Following Laing O'Rourke's contribution to the birth of Systems Engineering in infrastructure in the Terminal 5 programme at Heathrow Airport, the company has continued to invest in systems engineering and digital capability, leading development across key infrastructure projects — the London 2012 Olympics, Crossrail and now High Speed 2. These are all projects that have played a key part in the development of BIM standards, and supported key government initiatives — including the Avanti Programme, the UK BIM Task Group and the Centre for Digital Built Britain.

Our partnership with the Imperial Centre for Systems Engineering and Innovation is a striking example of continued commitment to digital innovation. It provided emerging insights on design changes using BIM data, network analyses and co-modelling approaches. Other new methods included: addressing productivity in construction; construction progress monitoring and tracking; and, practical advice on how to use shared visualization of data, often across different disciplines.

New knowledge: unlocking future opportunities

With access to the Centre's latest research and thinking, this knowledge has influenced Laing O'Rourke's strategy and approach, with new skill sets being developed within the company.

These have been applied to improve our delivery programmes, and support our projects, which are the beating heart of the business. As we have further extended and developed our expertise within Laing O'Rourke, we have applied these new techniques and skills in various other areas. This has unlocked a series of opportunities.

New nuclear: using Modern Methods of Construction

The centre supported Laing O'Rourke's research to extend MMC principles into Nuclear New Build inspired through our involvement in the Hinkley Point C nuclear power station project, and other programmes such as the Rolls-Royce led Low Cost Nuclear Small Modular Reactor LOR engaged PhD researcher Dr Jean Paul Vella - through its connections to the Centre - to develop connection methods which would extend our 'kit of parts' approach, and unlock increased productivity in seismically qualified Nuclear construction.

This project had three key objectives:

- Reduce the width of joint connections between precast concrete slab panels, to reduce the time and cost onsite.
- Reduce the need for the conventional formwork and propping, to temporarily support the structure while the joint develops the specified strength.
- Validate the structural reliability of the off-site MMC modular approach in the nuclear environment.

Designs produced from the research have been adopted across a broad range of products and solutions - manufactured offsite for construction and infrastructure projects at LOR's modern centre of construction excellence at Explore Industrial Park,. Jean -Paul Vella has joined the Laing O'Rouke team to help transfer this learning directly into practical application.

Planning and logistics research benefitting Hinkley Point C

Working closely with the Centre's Professor Washington Ochieng and Dr Panagiotis Angeloudis, construction planning and logistics research has benefitted and aided the construction of the Hinkley Point C nuclear project, and, their operations in the Precast Yard.

The first research project resulted in the development of a microsimulation model, which focused on the multimodal logistics of urban construction projects. The model had the ability to plot a route for prefabricated component shipments through rivers and waterways, to meet construction sustainability goals set by the UK Government. This model served as the foundation of the Delos simulation engine, which has been in continued development since then, and has since been used by more than 10 researchers as their primary 'experimentation sandbox' for logistics and mobility studies.

The second of Professor Washington Ochieng and Dr Panagiotis Angeloudis' research projects, developed an automated layout planning tool which has been deployed on the Hinkley Point C construction site. It is also used to coordinate the casting of building components, considering the lifting equipment available, construction schedules and safety restrictions.

Other projects have created simulation models to support tower crane performance and improve efficiencies across the vast site in Somerset.

Images
Hinkley Point C, EDF Group

Super yacht technology meets the architectural challenge at Bishopsgate Unique Structural Solutions

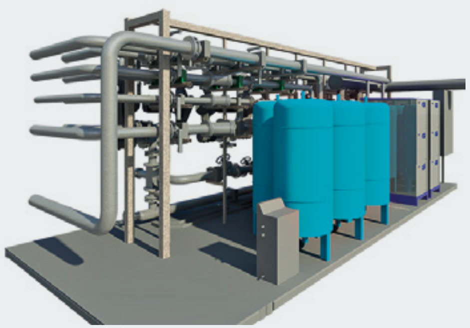
Systems Engineering principles were the key to addressing a complex engineering and supply chain challenge on 150 Bishopsgate. The project, to construct a central London tower, was fulfilled by Laing O'Rourke's concrete structure specialists in Expanded. The architectural requirement was to support the corners of each floor plate all the way up the tower, which has a bold stainless steel 'exoskeleton' similar to a tall ship rigging system. By having rigorous systems engineering principles in place, it ensured that detailed requirements and explicit verification and validation methodologies were used to develop the design.

The rigour in LORs approach also fully supported the manufacturing, supply chain and site assembly processes. The resulting solution brought leading-edge technologies from the worlds most advanced super yachts, safely into the construction environment.

Advancing MMC modular solutions for new Schools

Systems Engineering principles are central to Laing O'Rourke's R&D strategy, along with the continued development of modular building products and solutions. Laing O'Rourke has collaborated with the Centre on some of the key MMC innovations on recent schools' projects. Laing O'Rourke scholars from the Centre conducted research, and developed solutions to aid the design process.

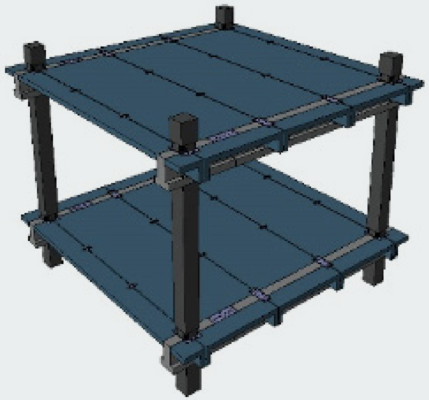
One example was Irek Starzk, a graduate of the Masters in Systems Engineering and Innovation programme, who developed an approach that utilised digital technology to visualise the plant room assembly process. This led to a series of 'packaged plantroom' solutions, that have improved productivity by 50%, and established a platform system for LORs new school development projects.



Left
Parametric tool for the design of modular plant-rooms. Delivery will require a step change in parts of its supply chain

Right
150 Bishopsgate

Modular construction
Laing O'Rourke is a leader in offsite modular production methods



Prefabricated concrete frames
Prefabricated concrete frames - Laing O'Rourke has worked with Imperial College London on innovative jointing methods

Advancing MMC modular solutions for housing

Laing O'Rourke has developed an advanced manufactured housing solution which will transform the sector. Steel framed housing modules will be precision-manufactured in a highly automated facility, resulting in residential apartment buildings which will be 95% complete within the factory environment, with a 95% reduction in terms of labour costs and on-site construction time.

Laing O'Rourke's Advanced Manufacturing Facility (AMF) relies on the application of Systems Engineering to create configurable products and provides the essential technical integrity required. The AMF has enough system flexibility to meet a wide range of client requirements, and with highly automated manufacturing processes which operate to the highest standards, the beneficiaries will be future residents. The design and engineering programme has been led by Doug Baldock, a Masters graduate from the Centre, who joined Laing O'Rourke to deliver the project.

Advancing re-usable structural solutions for ultra-fast construction.

Laing O'Rourke has developed a new, patented structural system that can be built up to 4 times faster and saves up to 70% of embodied CO_2 when compared to a traditional structural system.

A key feature of this 'D-Frame' system is the connection development and testing which was completed following a systems engineering methodology with the Imperial College Civil Engineering department. This enables the structure to be simply 'deconstructed' and re-used or re-configured supporting the principles of the circular carbon economy.

Executive level education to advance the industry

Not only has Laing O'Rourke supported t he Centre by developing engineering skills throughout the industry, via the Laing O'Rourke Scholarship Programme, a Systems Engineering Leadership Programme has also been developed.

The latter programme is designed to develop systems engineering leadership in the delivery of built infrastructure. The programme covers:

- The fundamentals of systems thinking and systems engineering
- The role and contribution of systems engineering — to address the challenges required to transform the construction industry, while creating safe places for users of the built environment
- Technical leadership skills — for using systems engineering in the delivery of the built infrastructure

This development programme has already benefited both Laing O'Rourke staff and over 200 other industry Professoressionals.

In conclusion: 10 years of the construction value-chain

Throughout the 10 years of support — via the complete end to end construction value chain we've undertaken — Laing O'Rourke has provided both fertile research (and reference territory) for the Centre's team, as they developed their leading-edge capabilities.

Laing O'Rourke will continue to support the Centre as it evolves to address the challenges of the next 10 years.

By supporting the application of Systems Engineering and Innovation, throughout the construction sector, we hope to continue enabling successful delivery of the most complex projects in the future.

Benefits and outcomes

Alumni

One of the outcomes of our research is trained experts, researchers who have worked with us at post-doctoral level, PhD students and MSc students, who have learnt about systems engineering with us, and take that knowledge out into the industry.

Dr Mikela Chatzimichailidou
PhD, MSc, MEng, MIET, IPMA, is currently the R&D Functional Lead for the Systems Engineering and Assurance Directorate and a Team Leader at WSP.

Mikela joined the Centre for Systems Engineering and Innovation (CSEI), Imperial College London as a Postdoctoral Research Associate in November 2017. She undertook research on the development of a systems engineering toolkit for delivering complex infrastructure projects. Moreover, she started exploring the possible links between modular production and systems engineering. Previously, she was a Postdoctoral Research Associate at the Centre for Transport Studies (CTS). Throughout her time at Imperial College, she was responsible for the CTS seminars, as well as being an active postdoc representative for the Department of Civil Engineering. Before joining Imperial College, she was a Postdoctoral Research Associate at the Engineering Design Centre, University of Cambridge.

Mikela's specialty in systems engineering and safety is coupled with an extensive record of publications. She has published a book and a research report in collaboration with the CSEI, Innovate UK, Catapult and the KTN. She has also published 14 peer reviewed papers in international journals, as well as delivering over 40 conference papers.

Her research activities strongly complement her presence in industry and her vision is to bridge the gaps between academia and industry. Her favourite saying is: "Once Imperial always Imperial"!

Dr Jean Paul Vella
Is currently a Structural Engineer in Laing O'Rourke.

Having graduated as a Bachelor of Architecture and Civil Engineering from the University of Malta in 2010, in 2011, he enrolled into a full time MSc course in General Structural Engineering at Imperial College, achieving a pass with distinction. Jean Paul's achievements from the MSc course included first prize in the Imperial College Student Concrete Design Competition, awarded by the Institution of Structural Engineers for his work on the design of a concrete tall building as his thesis project, and the Gyebi Kufuor Memorial Prize awarded by Imperial College for excellence in Concrete Structures and Technology.

After a stint in industry back in Malta, Jean Paul returned to Imperial College in November 2013 as a PhD student within the Centre for Systems Engineering and Innovation working on research into headed bar connections between precast concrete elements. The research was sponsored by Laing O'Rourke and proved to be very exciting due to the direct links with industry and potential for impact on construction practice.

The PhD provided a stepping-stone into Laing O'Rourke where Jean Paul is currently a Structural Engineer within the Engineering Excellence Group working on challenging projects involving research and development opportunities, helping push forward the company's innovation agenda.

Doug Baldock
MSc in Systems Engineering and Innovation at the CSEI between 2012-2014.

Prior to undertaking his MSc, Doug graduated with a first-class honours in Mechanical Engineering from Brunel University in London. After graduating, he joined building services consultancy Hoare Lea in Bristol, and relocated to London in 2013 to lead the mechanical engineering system designs for a number of high-profile high rise residential buildings in the capital.

The decision to apply for the MSc was taken based on a desire to undertake a course that offered a unique opportunity to study at a world class institution and experience teaching from a variety of departments within the College. In Doug's words "there was no other course in the country that offered so much variety and quality of teaching at the time. This was an opportunity to differentiate myself". Doug's thesis discussed downscaling urban energy system optimisation models to more localised projects, which was tested on the Imperial College White City Campus. Doug presented his findings at the CIBSE Technical Symposium at UCL in London.

Systems thinking is critical in tackling the complexity and productivity challenges the industry is facing says Doug: "It's imperative that we embrace these new ways of working if we really want to make a difference". The opportunity to use his skills in practice has come since joining Laing O'Rourke in 2017 where Doug currently leads the mechanical, electrical and plumbing (MEP) design and engineering for the company's advanced manufactured modular housing product.

Outreach and activities

We run annual events to showcase the research of the Centre and engage with industry and policy. These have attracted a growing audience, with recent events having hundreds of participants. Other activities, such as masterclasses, are invitation only.

10

Showcase events & distinguished lectures

2020 10-Year Celebration
7 July [keynotes Professor David Gann, Imperial College London, Ray O'Rourke, Laing O'Rourke and Nadhim Zahawi, Minister for Construction].

2019 Showcase
Systems Approaches to Transforming Construction, 14 November [keynotes Ivan Lucic, Network Rail and Phil Wilbraham, Heather Expansion Programme].

2018 Showcase
Infrastructure Interdependencies in London, 7 September [keynotes David Hancock, Construction Director, IPA and Judith Hackitt, author of Building Safely by Design]

2017 Showcase
Production Systems, Interdependencies and Transitions from the project to operations, 8 September [keynotes Professor Hillary Sillitto, Sillitto Enterprises].

2016 Inaugural
Professor Whyte's inaugural lecture "Starting with the End in Mind", May 26 2016

2015 Distinguished Lecture
Resilience: A systems engineering perspective. Professor David Oxenham, Ministry of Defence. 4 March 2015

Keynotes

We have presented at well over 100 conferences, industry and policy events over the last 10 years. Selected keynote and other invited lectures from the members of the CSEI include:

Gordon Research Seminar on Advanced Materials for Sustainable Infrastructure Development Session Chair 2020. (Dr Rupert J. Myers)

Invited speaker at the Futurebuild "Water Challenges for the UK" session, London, March 2019. (Dr Ana Mijic)

Opening Panel, with chair of Construction Leadership Council, Construction Minister and Infrastructure Projects Authority, *FT Future of Construction Summit*, 23 May 2019, Institution of Civil Engineers, London, UK. (Professor Jennifer Whyte)

UK-China Workshop: Novel Utilization of Mining Wastes in Construction Materials Keynote 2019. (Dr Rupert J. Myers)

Closing Keynote "Innovation and its potential: changing organisational cultures and processes", National Housing Federation *Housing Finance Conference*, 21 March 2019, Liverpool, UK. (Professor Jennifer Whyte)

Invited speaker at the Westminster Business Forum "Future prospects for the water market and development towards PR19" event, London, June 2018. (Dr Ana Mijic)

Invited Oral evidence to Lord's Select Committee Inquiry on Offsite Manufacturing for Construction, 24 April 2018, House of Commons, London, UK. (Professor Jennifer Whyte) http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/science-and-technology-committee-lords/offsite-manufacture-for-construction/oral/82167.html

Invited speaker at Advanced Propulsion Centre Future of Technology series, 2018. (Dr Mark Stettler)

Invited speaker at World Economic Forum in Tianjin, 2018. (Dr Mark Stettler)

UK-China workshop: Urban Flooding and Sponge Cities Keynote, Shenzhen 2017. (Dr Ana Mijic)

Top
2017 Showcase

Left
2018 Showcase

Right
2019 Showcase

Systems engineering leadership

22 March 2019
25 attendees from companies Arup, Costain Ltd, Dubai Petroleum, Frazer-Nash Consultancy Ltd, Laing O'Rourke, Mott MacDonald, Ove Arup & Partners Ltd and Transport for London

27 September 2019
20 attendees from companies Autodesk Research, Laing O'Rourke, Mott MacDonald and University of Cambridge

Seminar series

1. Building retrofit product innovation: Identifying trends using patent and policy data, Dr Kate Simpson, 7 October 2020
2. A Framework for Assessing Public Occupancy Risk in Buildings, Georgia Bateman, 30 September 2020
3. Distinguished Systems Integration Masterclass, Professor Olivier De Weck, MIT and Andrew Wolstenholme, 23 September 2020
4. Hoping for the Best and Planning for the Worst, Professor Martin Mayfield, University of Sheffield, 20 May 2020
5. Sustainable Living Places: Infrastructure systems, stakeholders and shared perspective, Dr Corina Shika Kwami, Royal Academy of Engineering, 22 April 2020
6. Designing with Natural Ventilation in Challenging Climates, Professor Malcolm Cook, Loughborough University, 19 February 2020
7. Lean Production System Innovations in Construction, Professor Rafael Sacks, Israel Institute of Technology, 16 October 2019
8. Automatically Generating Structured Information on the As-is Status of Facilities from Visual Data, Iro Armeni, Stanford University, 2 July 2019
9. Innovation in industrialised construction from Silicon Valley, Assistant Professor Daniel Hall, ETH Zurich, 18 June 2019
10. Orchestration Inter-Organisational Networks to Deliver Megaprojects, Professor Jens Roehrich, University of Bath, 22 May 2019
11. Capturing Stakeholder Value for Design of Built Environment, Professor Koshy Varghese, Indian Institute of Technology Madras, 17 April 2019
12. Challenges for Engineering Resilience, Professor Liz Varga, Cranfield School of Management, 20 February 2019
13. Improving Supply Chain Integration for Infrastructure Projects, Professor Jan Godsell, University of Warwick, 27 November 2018
14. Hybrid Reality Spaces - Visually and Structurally Mixed Reality, Associate Professor Frédéric Bosché, Heriot Watt University, 19 September 2018
15. Coping with Heterogeneous Information in Building and Construction Projects — Big Open BIM with Linked Data, Professor Jakob Beetz, University Aachen, 15 August 2018
16. Cognitive Built Environments at the Convergence of Sensing, Systems Thinking, and Data Science, Associate Professor Burcin Becerik-Gerber, University of Southern California, 20 June 2018
17. BIM LogMining: Application of Data Science/Social Network Analysis in Design Productivity Assessment, Associate Professor Baabak Ashuri, Georgia Institute of Technology, 29 May 2018
18. A Hitchhiker's Guide to Complexity: The Case of Engineering Projects, Dr. Christos Ellinas, University of Bristol, 23 April 2018
19. Advancing Construction: Pursuing Integrated Teams through Procurement, Organization, and Technology, Associate Professor Dr Robert M. Leicht, Penn State. 14 Mar 2018
20. Buried Infrastructures in Civil System, Dr. Léon olde Scholtenhuis, University of Twente, 21 February 2018
21. Systems Engineering in the Civil Engineering industry, Assistant Professor Robin de Graaf, University of Twente, 24 January 2018
22. Swimming Across Lanes, Professor Raymond Levitt, Stanford University, 4 October 2017
23. Virtualizing Infrastructure, Dr Ioannis Brilakis, University of Cambridge, 27 September 2017
24. Supporting Product Development through Automatically Generated Design Structure Matrices, James Gopsill, University of Bristol, 19 July 2017
25. Five Simple Rules for Innovation in Megaprojects, Professor Mark Dodgson, University of Queensland, 28 June 2017
26. Infrastructure as a Purposeful Complex System, Dr Neil Carhart, University of Bristol, 24 May 2017
27. System-of-Systems Methodology for National Infrastructure Assessment, Professor Jim Hall, University of Oxford, 09 November 2016
28. If the Answer is "Let's build small modular nuclear reactors" What Exactly is the Question? Dr Giorgio Locatelli, University of Leeds, 02 November 2016
29. How Project Integration Strategies Impact the Adoption of Systemic Innovations, Mr Dan Hall, Stanford University. 05 Oct 2016
30. Infrastructure System-of-Systems: A Holistic Paradigm for Sustainable and Resilient Civil Systems, Assistant Professor Ali Mostafavi, Florida International University. 01 Jul 2016
31. BIM — a physical, personnel and cyber security challenge, Honorary Principal Research Fellow Paul Forman, Imperial College London. 08 Mar 2016
32. Systems Engineering for a Sustainable Built Environment, Assistant Professor Philipp Geyer, KU Leuven. 10 Feb 2016
33. BIM workshop, Ghang Lee, Yongsei, Zhiliang Ma, Tsinghua and students, 20 January 2016
34. Real Options & Flexibility in Engineering Design, Michel-Alexandre Cardin, NUS, 26 November 2016
35. Redesigning Project Management, John Heintz, TU Delft, 26 November 2015

Our people

Our people

Centre Directors
Dr Ana Mijic
Centre Co-Director, Senior Lecturer in Water Systems Integration

Professor Jennifer Whyte
Centre Co-Director, Laing O'Rourke & Royal Academy of Engineering Chair in Systems Integration

Professor Washington Ochieng
Centre Executive Director and Professor in Positioning and Navigation Systems

Professor David Fisk
Centre Founding Director and Emeritus Chair in Systems Engineering and Innovation

Jeni Giambona
Research and Engagement Manager

Tim Gordon
Centre Administrator

Internal Management Group
Dr Panagiotis Angeloudis
Reader in Transport Systems and Logistics

Dr Michel-Alexandre Cardin
Senior Lecturer in Computational Aided Engineering

Dr John Craske
Lecturer in Fluid Mechanics

Dr Luigi Mosca
Research Associate

Dr Rupert J. Myers
Lecturer in Sustainable Materials Engineering

Dr Marc Stettler
Senior Lecturer in Transport and the Environment

Dr Kate Simpson
Research Associate

Dr Ivan Stoianov
Reader in Water Systems Engineering

Advisory Board
Professor Atula Abeysekera
Imperial College London

Nabil Abou-Rahme
Chief Research Officer, Bentley Systems

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Imperial College London

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Imperial College London

Maggie Brown
Commercial Lead-Supplier Relationship Management, EDF

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Professor of Concrete Structures and Head of the Department of Civil & Environmental Engineering
Imperial College London

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Senior Policy Advisor
Royal Academy of Engineering

Professor Brian Collins
Professor of Engineering Policy at UCL, Director of the International Centre for Infrastructure Futures
UCL

Dr Mike Cook
Project Principal
Buro Happold

Adam Locke
Partnership and Innovation Leader, Engineering Excellence Group
Laing O'Rourke

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Editor in Chief
Buildings and Cities

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Emeritus Professor of Civil Engineering
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Imperial College London

Juliet Mian
Technical Director, Resilienceshift

Dr Chris Millard
Head of Engineering Excellence, Laing O'Rourke

Ed Pound
Executive Director, Project Production Institute

Professor Christopher Tucci
Professor of Digital Strategy and Innovation

Associated Faculty
Professor Christopher Cheeseman
Professor of Materials Resources Engineering

Professor Tim Green
Director of the Energy Futures Laboratory (EFL)

Dr Sunday Popo-Ola
Research and Teaching Fellow
Imperial College London

Dr Arnab Majumdar
Reader in Transport Risk Management
Imperial College London

Professor Nilay Shah
Professor of Process Systems Engineering
Imperial College London

Professor Stephen Smith
Professor of Bioresource Systems
Imperial College London

Dr Aruna Sivakumar
Senior Lecturer in Travel Behaviour and Urban Systems Modelling
Imperial College London

Dr Hong Wong
Reader in Structures and Materials
Imperial College London

Professor Robert Vollum
Professor in Concrete Studies
Imperial College London

Our people

Associated Postdoctoral Research Fellows and Research Assistants

1. Dr Ranjith Soman, Research Associate, (Imperial College London), AEC Production Control Room, Innovate UK, September 2020-to date.

2. Dr Karim Farghaly Research Associate, (Imperial College London), AEC Production Control Room, Innovate UK, August 2020-to date.

3. Dr Kate Simpson, Research Associate (Imperial College London/Alan Turing Institute), Retrofit Design, February 2019-to date.

4. Dr Leo Hsu, Research Associate (Imperial College London/Alan Turing Institute), Data-Driven Design of Urban Mobility and Civil Infrastructure Systems, August 2018-to date.

5. Dr Luigi Mosca, Research Associate (Imperial College London), Transforming Construction Network Plus, December 2018-to date.

6. Marcus Wallbaum, Research Assistant (Imperial College London/Alan Turing Institute), Computer Vision, July 2019-February 2021.

7. Dr Annie Wang, Research Associate (Imperial College London), December 2019-July 2020, became Lecturer at Loughborough University.

8. Dr Chen Long, Research Associate (Imperial College London/Alan Turing Institute), October 2018-July 2020, became Lecturer at Loughborough University.

PhD students

1. Zhu, Hongmin, *Predicting failure rates in repairable and redundant infrastructure systems* (Full time PhD, starting May 2019, Dixon Award), supervisors Jennifer Whyte, Christian Onof, Pan Angeloudis.

2. Shanjing (Alexander) Zhou, *Digitally-enabled product platform strategies: industrialized building firms, modularity and open innovation* (Full time PhD, starting January 2019), supervisors Jennifer Whyte, Luigi Mosca, Long Chen.

3. Zhang, Ruoheng, *Building capacity for systems integration in digitally enabled modular building* (Full time PhD, started October 2018, Dixon Award, RAEng Regional Award co-funding). Interruption of studies until June 2020.

4. Saeed Tahmasebi Khademasadi, *A systems engineering approach to off-site production: from requirements to customer solution*, Laing O'Rourke (Part-time PhD, June 2018-January 2020). https://www.imperial.ac.uk/giving/donate/remembering-saeed/

5. Tim Haughton (October 2017-June 2021) *Optimisation of Modularisation and Construction Scheduling of Small Nuclear Reactors* (Imperial College London & Rolls Royce) EPSRC Industrial CASE PhD Studentship, supervisors Dr Panagiotis Angeloudis (Civil & Environmental Engineering) and Dr Panos Parpas (Computing).

6. Niki Avgeraki (October 2017-June 2021) *Economics of manufacturing small modular reactors*, Staffell, Iain (Centre for Environmental Policy) first supervisor; other supervisors Locatelli and Whyte.

7. Ranjith Soman (Feb 2017-Aug 2020) *codifying information flow in 'construction as a manufacturing process' in BIM-enabled projects to support future automation* (supervisors Whyte and Molina Solana) Skempton Scholarship, Bentley Systems 50% co-funding.

8. Tanawan Wee, (PhD, April 2015) second supervisor from November 2015, co-supervisors Marco Aurisicchio, Jennifer Whyte.

Recent Visiting Faculty

1.Dr Vincent Gan, visiting lecturer from Hong Kong University of Science and Technology, October-November 2019.

2. Dr Léon olde Scholtenhuis, visiting lecturer from University of Twente, January-March 2018.

3. Professor Wei Pan, Executive Director of HKU Centre for Innovation in Construction, Hong Kong University, 2015.

Recent Visiting PhD Students

4. Mi Pan, visiting PhD from Hong Kong University (Advisor Wei Pan) *A multifaceted examination of the future potentialities and innovation processes of construction robots*, visiting April-May 2019.

5. Sidsel Katrine Ernstsen, visiting PhD from Danish Technical University (DTU), September 2018.

6. Dan Hall, Stanford University (Advisor: R.E. Levitt; Committee: M. Fischer; C.S. Dossick) *Assessing the impact of project integration strategies on integral innovations* visiting October-December 2016, Imperial.

Accessing our research

Accessing our research

Our research is widely published in leading international journals, and we have recently published on our forward research agenda.

Whyte, J., Mijic, A., Myers, R. J., Angeloudis, P., Cardin, M. A., Stettler, M. E. J. & Ochieng, W. (2020). A Research Agenda on Systems Approaches to Infrastructure. *Civil Engineering and Environmental Systems*. https://doi.org/10.1080/10286608.2020.1827396

Journal Publications

1. Angeloudis, P. & Fisk, D. (2006) Large subway systems as complex networks. *Physica A: Statistical Mechanics and its Applications*. 367, 553–8. https://doi.org/10.1016/j.physa.2005.11.007

2. Anvari, B., Angeloudis, P. & Ochieng, W.Y. (2016) A multi-objective GA-based optimisation for holistic Manufacturing, transportation and Assembly of precast construction. *Automation in Construction*. 71, 226–41. https://doi.org/10.1016/j.autcon.2016.08.007

3. Babovic, F., Mijic, A. & Madani, K. (2018) Decision making under deep uncertainty for adapting urban drainage systems to change. *Urban Water Journal*. 15 (6), 552–60. https://doi.org/10.1080/1573062X.2018.1529803

4. Brookes, N., Sage, D., Dainty, A., Locatelli, G. & Whyte, J. (2017) An island of constancy in a sea of change: Rethinking project temporalities with long-term megaprojects. *International Journal of Project Management*. 35 (7), 1213–24. https://doi.org/10.1016/j.ijproman.2017.05.007

5. Cardin, M.-A. (2014) Enabling Flexibility in Engineering Systems: A Taxonomy of Procedures and a Design Framework. ASME Journal of Mechanical Design, 136(1), 1-14. doi: 10.1115/1.4025704

6. Cardin, M.-A., Xie, Q., Ng, T. S., Wang, S., & Hu, J. (2017) An approach for analyzing and managing flexibility in engineering systems design based on decision rules and multistage stochastic programming. IISE Transactions, 49(1), 1-12. doi: 10.1080/0740817X.2016.1189627

7. Caunhye, A. M., & Cardin, M.-A. (2017) An Approach based on Robust Optimization and Decision Rules for Analyzing Real Options in Engineering Systems Design. IISE Transactions, 49(8), 753-767. doi: 10.1080/24725854.2017.1299958 — 2019 IISE Transactions Best Paper in Design & Manufacturing

8. Chatzimichailidou, M.M., & Dokas, I.M. (2016) Risk SOAP: On the Relationship Between Systems Safety and the Risk SA Provision Capability. *IEEE Systems Journal*. 12 (2), 1–10. https://doi.org/10.1109/JSYST.2016.2614953

9. Comi, A., Jaradat, S. & Whyte, J. (2019) Constructing shared Professoressional vision in design work: The role of visual objects and their material mediation. *Design Studies*. 35 (1), 18–27. https://doi.org/10.1016/j.destud.2019.06.003

10. Comi, A., & Whyte, J. (2017) Future Making and Visual Artefacts: An Ethnographic Study of a Design Project. *Organization Studies*. 39 (8), 1055–83. https://doi.org/10.1177/0170840617717094

11. De Stercke, S., Chaturvedi, V., Buytaert, W. & Mijic, A. (2020) Water-energy nexus-based scenario analysis for sustainable development of Mumbai. *Environmental Modelling & Software*.134, 104854. https://doi.org/10.1016/j.envsoft.2020.104854

12. De Stercke, S., Mijic, A. Buytaert, W. 7 Chaturvedi, V. (2018) Modelling the dynamic interactions between London's water and energy systems from an end-use perspective. *Applied Energy*. 230, 615–26. https://doi.org/10.1016/j.apenergy.2018.08.094

13. Dobson, B. & Mijic, A. (2020) Protecting rivers by integrating supply-wastewater infrastructure planning and coordinating operational decisions. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/abb050

14. Ernstsen, S., Whyte, J., C., T. & & Maier, A. (Forthcoming). How innovation champions frame the future: three visions for digital transformation of construction. *Construction Engineering and Management*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001928

15. Fisk, D. (2016) 'Feedback Exergy exegesis', *Physics World*. 29(2), 20. https://doi.org/10.1088/2058-7058/29/2/26

16. Fisk, D. (2004) Engineering complexity. *Interdisciplinary Science Reviews*. 29 (2), 151–61. DOI: https://doi.org/10.1179/030801804225012617

17. Fisk, D. (2017) Deep thought. *Physics World*. 30 (8), 18. https://doi.org/10.1088/2058-7058/30/8/31

18. Fisk, D., & Kerherve, J. (2006) Complexity as a cause of unsustainability. *Ecological Complexity*. 3 (4), 336–43. https://doi.org/10.1016/j.ecocom.2007.02.007

19. Goldbeck, N., Angeloudis, P. & Ochieng, W.Y. (2019) Resilience assessment for interdependent urban infrastructure systems using dynamic network flow models. *Reliability Engineering & System Safety*. 188, 62–79. https://doi.org/10.1016/j.ress.2019.03.007

20. Hall, D.M., Whyte, J. & Lessing, J. (2019) Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study. *Construction Management and Economics*. 38 (4), 322-339. https://doi.org/10.1080/01446193.2019.1656814

21. El Hattab, M.H., Theodoropoulos, G., Rong, X. & Mijic, A. (2020) Applying the Systems Approach to Decompose the SuDS Decision-Making Process for Appropriate Hydrologic Model Selection. *Water*. 12 (3), 632. https://doi.org/10.3390/w12030632

22. Hsu, P.-Y., Aurisicchio, M., Angeloudis, P. & Whyte, J. (2020) Understanding and visualizing schedule deviations in construction projects using fault tree analysis. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-01-2020-0058

23. Hsu, P.Y., Angeloudis, P. & Aurisicchio, M. (2018) Optimal logistics planning for modular construction using two-stage stochastic programming. *Automation in Construction*. 94, 47–61. https://doi.org/10.1016/j.autcon.2018.05.029

24. Iuorio, O., Wallace, A. & Simpson, K. (2019) Prefabs in the North of England: Technological, Environmental and Social Innovations, *Sustainability*. 11 (14), 1–14. https://doi.org/10.3390/su11143884

25. Kia, A., Wong, H.S. & Cheeseman, C.R. (2020) High-strength clogging resistant permeable pavement. *International Journal of Pavement Engineering*. 1-12 https://doi.org/10.1080/10298436.2019.1600693

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26. Kuznetsova, E., Cardin, M.A., Diao, M. & Zhang, R. (2019) Integrated decision-support methodology for combined centralized-decentralized waste-to-energy management systems design. *Renewable & Sustainable Energy Reviews*. 103, 477–500. https://doi.org/10.1016/j.rser.2018.12.020

27. Lobo, S. & Whyte, J. (2017) Aligning and Reconciling: Building project capabilities for digital delivery. *Research Policy*. 46 (1), 93–107. https://doi.org/10.1016/j.respol.2016.10.005

28. Lord, S.F., Noye, S., Ure, J., Tennant, M. & Fisk, D. (2016) Comparative review of building commissioning regulation: a quality perspective. *Building Research and Information*. 44 (5-6), 630-43. https://doi.org/10.1080/09613218.2016.1181955

29. Lu, Q., Chen, L., Li, S. & Pitt, M. (2020) Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Automation in Construction*. 115 (103183), 1–19. DOI: https://doi.org/10.1016/j.autcon.2020.103183

30. Martinetti, A., Chatzimichailidou, M.M., Maida, L. & van Dongen, L. (2018) Safety I–II, resilience and antifragility engineering: a debate explained through an accident occurring on a mobile elevating work platform. *International Journal of Occupational Safety and Ergonomics*. 25 (1), 66–75. https://doi.org/10.1080/10803548.2018.1444724

31. McMillan, H., Montanari, A., Cudennec, C., Savenije, H., Kreibich, H., Krueger, T., Liu, J., Mejia, A., Van Loon, A., Aksoy, H., Di Baldassarre, G., Huang, Y., Mazvimavi, D., Rogger, M., Sivakumar, B., Bibikova, T., Castellarin, A., Chen, Y., Finger, D., Gelfan, A., Hannah, D. M., Hoekstra, A. Y., Li, H., Maskey, S., Mathevet, T., Mijic, A., Pedrozo Acuña, A., Polo, M. J., Rosales, V., Smith, P., Viglione, A., Srinivasan, V., Toth, E., van Nooyen, R. and Xia, J. (2016). Panta Rhei 2013–2015: global perspectives on hydrology, society and change. *Hydrological Sciences Journal*. 61 (7), 1–18. https://doi.org/10.1080/02626667.2016.1159308

32. Nikolić, D., Maftei, L. & Whyte, J. (2019) Becoming familiar: how infrastructure engineers begin to use collaborative virtual reality in their interdisciplinary practice. *IT in Construction (ITcon)*. 24, 489–508. https://doi.org/10.36680/j.itcon.2019.026

33. Noye, S., North, R. & Fisk, D. (2016) Smart systems commissioning for energy efficient buildings. *Building Services Engineering Research and Technology*. 37 (2), 194–204. https://doi.org/10.1177/0143624415622954

34. Noye, S., North, R. & Fisk, D. (2018) A wireless sensor network prototype for post-occupancy troubleshooting of building systems. *Automation in Construction*. 89, 225–34. https://doi.org/10.1016/j.autcon.2017.12.025

35. Ossa-Moreno, J., Smith, K.M. & Mijic, A. (2017) Economic analysis of wider benefits to facilitate SuDS uptake in London, UK. *Sustainable Cities and Society*. 28, 411–9. https://doi.org/10.1016/j.scs.2016.10.002

36. Pamenter, S., & Myers R.J. (accepted) Decarbonising the cementitious materials cycle; a whole-systems review of measures to decarbonise the cement supply chain in the UK and European contexts. *Journal of Industrial Ecology*.

37. Sacks, R., Whyte, J., Swissa, D., Raviv, G., Zhou, W. & Shapira, A. (2015) Safety by design: dialogues between designers and builders using virtual reality. *Construction Management and Economics*. 33 (1), 55–72. https://doi.org/10.1080/01446193.2015.1029504

38. Santos, P.L.C.T., Monteiro, P.A.A., Studic, M. & Majumdar, A. (2017) A methodology used for the development of an Air Traffic Management functional system architecture. *Reliability Engineering & System Safety*. 165, 445–57. https://doi.org/10.1016/j.ress.2017.05.022

39. Shi, F., Soman, R. K., Han, J. & Whyte, J. (2020) Addressing adjacency constraints in rectangular floor plans using Monte-Carlo Tree Search. *Automation in Construction*.115, 103187. DOI: https://doi.org/10.1016/j.autcon.2020.103187

40. Simpson, K., Whyte, J. & Childs, P. (2020) Data-centric innovation in retrofit: A bibliometric review of dwelling retrofit across North Western Europe. *Energy and Buildings*. 229, 110474. https://doi.org/10.1016/j.enbuild.2020.110474

41. Soman, R. & Whyte, J. (2020) Codification challenges for data science in construction. *Journal of Construction Engineering and Management*. 146 (7). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001846

42. Soman, R. K., Molina-Solana, M. & Whyte, J. (2020) Linked-Data based Constraint-Checking (LDCC) to support look-ahead planning in construction. *Automation in Construction*. 120, 103369. https://doi.org/10.1016/j.autcon.2020.103369

43. Studic, M., Majumdar, A., Schuster, W. & Ochieng, W.Y. (2017) A systemic modelling of ground handling services using the functional resonance analysis method. *Transportation Research Part C: Emerging Technologies*. 74, 245–60. https://doi.org/10.1016/j.trc.2016.11.004

44. Tee, R., Davies, A. & Whyte, J. (2018) Modular designs and integrating practices: Managing collaboration through coordination and cooperation. *Research Policy*. 48 (1), 51–61. https://doi.org/10.1016/j.respol.2018.07.017

45. Tobaruela, G., Schuster, W., Majumdar, A. & Ochieng, W.Y. (2015) Framework to Assess an Area Control Centre's Operating Cost-efficiency: A Case Study. *Journal of Navigation*. 68 (6), 1088–1104. https://doi.org/10.1017/S0373463315000302

46. Whyte, J. (2015) Towards a new craft of architecture. *Building Research & Information*. 43 (2), 263–5. https://doi.org/10.1080/09613218.2015.962240

47. Whyte, J. (2018) Systems Engineering and the Project Delivery Process in the Design and Construction of Built Infrastructure. *Journal of Project Production Management*. Project Production Institute.

48. Whyte, J. (2019) How digital information transforms project delivery models. *Project Management Journal*. 50 (2), 177–94. https://doi.org/10.1177/8756972818823304

49. Whyte, J. & Hartmann, T. (2017) How digitizing building information transforms the built environment. *Building Research and Information*. 45 (6), 591–5. https://doi.org/10.1080/09613218.2017.1324726

50. Whyte, J., Lindkvist, C. & Jaradat, S. (2016) Passing the baton? Handing over digital data from the project to operations. *Engineering Project Organization Journal*. 6 (1), 2–14. https://doi.org/10.1080/21573727.2015.1115396

51. Whyte, J. & Nussbaum, T. (2020) Transition and Temporalities: Spanning Temporal Boundaries as Projects End and Operations Begin. *Project Management Journal*. 51, 505-521. https://doi.org/10.1177/8756972820919002

52. Whyte, J., Stasis, A. & Lindkvist, C. (2016) Managing change in the delivery of complex projects: Configuration management, asset information and 'big data'. *International Journal of Project Management*. 34 (2), 339–51. https://doi.org/10.1016/j.ijproman.2015.02.006

53. Whyte, J., Tryggestad, K. & Comi, A. (2016) Visualizing practices in project-based design: tracing connections through cascades of visual representations. *Engineering Project Organization Journal*. 6 (2-4), 115–28. https://doi.org/10.1080/21573727.2016.1269005

54. Wilke, S., Majumdar, A. & Ochieng, W.Y. (2014) Airport surface operations: A holistic framework for operations modeling and risk management. *Safety Science*. 63, 18–33. https://doi.org/10.1016/j.ssci.2013.10.015

55. Zhang, R., Zhou, S., Tahmasebi, S. & Whyte, J. (2019) Long-standing themes and new developments in offsite construction: The case of UK housing. *Proceedings of the Institution of Civil Engineers – Civil Engineering*. 176 (6), 29–35. https://doi.org/10.1680/jcien.19.00011

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Books and Book Chapters

56. Whyte, J. (2019) Smartphone as a mediating technology of organization. In: Beyes, T., Holt, R. & Pias, C. (eds.) *The Oxford Handbook of Media, Technology and Organization Studies. Oxford, Oxford University Press*. https://doi.org/10.1093/oxfordhb/9780198809913.013.35

57. Whyte, J. and Nikolic, D. (2018) *Virtual reality and the built environment*, 2nd edition, Routledge, Oxford, United Kingdom.

58. de Neufville, R., Smet, K., Cardin, M.-A., & Ranjbar Bourani, M. (2019) Engineering Options Analysis (EOA): Applications. In V. A. W. J. Marchau, W. E. Walker, P. J. T. M. Bloemen & S. W. Popper (Eds.), *Decision Making Under Deep Uncertainty: From Theory to Practice*. Cham, Switzerland, Springer. https://my.b-ok.as/book/5242501/8e1c7a

Conference Papers

59. Babovic, F., Chen, L., Gamble, C., Genes, C., Fitzgerald, J., Pierce, K., Punzo, G. & Whyte, J. (2019) A decision-tree for modelling approaches to use a digital twin in analysing systems interdependencies in infrastructure projects, Annual Systems Engineering Conference, 19—20 September 2019, Leeds, UK.

60. Balasubrahmani, M, Soman, R. K., Whyte, J. & Mahalingam, A. (2019) Temporality, innovation and megaproject-to-megaproject learning across continents in the case of Crossrail and Nagpur Metro. 35th European Group for Organizational Studies Colloquium, 1—6 July 2019, Edinburgh, UK.

61. Chatzimichailidou, M., & Whyte, J. (2018) Modular construction: Practical issues in dealing with complexity. 8th International Conference on Mass Customization and Personalization Community of Europe, 19—21 September 2018, Novi Sad, Serbia.

62. Chatzopoulou, M.A., Keirstead, J., Fisk, D. & Markides, C.N. (2016) Characterising the impact of HVAC design variables on buildings energy performance, using a Global Sensitivity Analysis Framework. CLIMA 2016 Conference, 22—25 May 2016, Aalborg, Denmark.

63. Chatzopoulou, M.A., Keirstead, J., Fisk, D. & Markides, C.N. (2016) Informing low carbon HVAC systems modelling and design, using a global sensitivity analysis framework. The American Society of Mechanical Engineers 10th International Conference on Energy Sustainability, 26—30 June 2016, Charlotte, North Carolina.

64. Chen, L, & Whyte, J. (2020) Analysing Interdependencies of Complex Engineering Systems using a Digital Twin-Driven Design Structure Matrix, 2020 ASCE Construction Research Congress (CRC 20), 8-10 March 2020, Temple, Arizona.

65. Grafius, D., Kim, H. & Whyte, J. (2017) Ecological interdependencies of infrastructure projects. International Symposium for Next Generation Infrastructure, Institution of Civil Engineers, 11—13 September 2017, London, UK.

66. Hsu, P.Y., Aurisicchio, M. & Angeloudis, P. (2017) Supply chain design for modular construction projects. Lean and Computing in Construction Congress - Volume 2: *Proceedings of 25th Annual Conference of the International Group for Lean Construction*, 9 July 2017, Heraklion, Greece.

67. Maftei, L., Nikolic, D. & Whyte, J. (2018) Challenges around integrating collaborative immersive technologies into a large infrastructure engineering practice. International Council for Research and Innovation in Building and Construction W78 IT in Design, Construction, and Management, 1—3 October 2018, Chicago, USA.

68. Nussbaum, T., Zerjav, V. & Whyte, J. (2018) Transition from project to operation in infrastructure megaprojects: Coordination by mutual adjustment. European Group for Organizational Studies, Sub-theme: 52: Projects for Innovation: Managing Novelty and Uncertainty, 5—7 July 2018, Tallinn, Estonia.

69. Owen, A., Janda, K.B. & Simpson, K. (2019) Who are the 'middle actors' in sustainable construction and what do they need to know? 5th Annual SEEDS conference, 11—12 September 2019, Leeds, UK.

70. Senthilvel, M., Soman, R.K., Mahalingam, A., Whyte, J., Raphael, B., Brilakis, I. and Varghese, K. (2018) Towards digital delivery of metro-rail projects in India. 7th World Construction Symposium 2018: Built Asset Sustainability: Rethinking Design, Construction and Operations, 29 June—01 July 2018, Sri Lanka.

71. Simpson, K. & Owen, A. (2019) Sustainable office construction processes and practices: An exploratory UK study. ARCOM, 2—4 September 2019, Leeds, UK.

72. Simpson, K. & Owens, A. (2018) Reflections from stakeholder engagement in developing a curriculum for sustainable renovation. SEEDS Conference, 6—7 September 2018, Dublin, Ireland.

73. Soman, R.K. (2019) Linked-data based dynamic constraint solving framework to support look-ahead-planning in construction. 36th International Council for Research and Innovation in Building and Construction W78 Conference on ICT in Design, Construction and Management in Architecture, Engineering, Construction and Operations (AECO), 18—20 September 2019, Newcastle, United Kingdom.

74. Soman, R.K. (2019) Modelling construction scheduling constraints using Shapes Constraint Language (SHACL). European Conference on Computing in Construction (EC^3 2019), 10—12 July 2019, Crete, Greece.

75. Soman, R.K., Birch, D. & Whyte, J. (2017) Framework for shared visualization and real-time information flow to the construction site. 24th European Group for Intelligent Computing in Engineering, 10-12 July 2017, Nottingham, United Kingdom.

76. Soman, R.K., & Whyte, J. (2017) A framework for cloud-based virtual and augmented reality using real-time information for construction progress monitoring. Lean and Computing in Construction Congress — *Volume 1: Proceedings of the Joint Conference on Computing in Construction*, 21 July 2017, Edinburgh, Scotland.

77. Studic, M. and Majumdar, A. (2015) Apron safety - A missing piece in the SESAR ConOps puzzle. In: Feary, M. & Feuerle, T. (eds.) ATACCS '15: *Proceedings of the 5th International Conference on Application and Theory of Automation in Command and Control Systems*, September 2015, Toulouse, France, pp. 32-40.

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