UNIVERSITY OF CAMBRIDGE

MAKING SMART INFRASTRUCTURE BUSINESS AS USUAL

Discussion Paper

Background

In February 2024 the Cambridge Centre for Smart Infrastructure and Construction (CSIC) organised a roundtable discussion with infrastructure clients, consultants, contractors, government and policy makers to understand why smart infrastructure is still not 'business as usual' – i.e. why smart infrastructures solutions are not fully exploited to bring maximum value to clients and their stakeholders. This paper summarises discussions at the roundtable and presents recommendations for action.

CSIC Cambridge Centre for Smart Infrastructure & Construction

1. Introduction: Smart Infrastructure

As defined in the paper, 'Smart Infrastructure Getting more from strategic assets' (2016) smart infrastructure is the result of combining physical infrastructure with digital infrastructure, providing improved information to enable better decision making. Smart Infrastructure enables us to gain value from data through analysis to deliver new insights on the design, performance, impact and integration of our infrastructure.

Smart infrastructure includes the combination of data generation, collection, curation and analysis technologies, which in this paper we refer to as smart solutions.

Smart infrastructure and data-centric engineering approaches bring many dimensions of value, including enabling better decision making for the whole life of our assets and systems, potentially de-risking and increasing quality of construction, increasing productivity and building confidence in the long-term performance of assets and systems. Most, if not all, infrastructure clients are reliant on smart solutions (e.g. SCADA systems, telemetry). However, levels of exploitation of smart solutions vary tremendously, from data gathering to predict and prevent, depending on a supply chain organisation's digital maturity. As a sector we are still not taking advantage of the full value that smart infrastructure can provide. Procurement and use of smart infrastructure solutions is still not business as usual. There are many individual examples of good practice, but adoption, whether in new or existing infrastructure, is still not widespread. What is holding our sector back from widespread, integrated, systemic adoption of smart infrastructure?

2. Understanding value in the infrastructure sector

Value is an abstract concept. It depends on the context of the project, asset, network or system and its scope and magnitude can change over time. Value is likely to be viewed differently by different stakeholders. This requires a flexible and adaptive approach to value management. Value can be expressed in terms of time, cost, quality, social, risk, carbon, and other factors that matter to decision-makers and stakeholders. Value has been defined or framed in a number of ways. The Construction Innovation Hub's Value Toolkit uses the Four Capitals Approach, Natural, Social, Human and Produced, as a way of defining value. This approach combines both qualitative and quantitative data to demonstrate how an organisation creates value for its stakeholders over time and enables decision making that gains the greatest value across all capitals. Another framework for assessing value is the Six Capitals Framework developed by International Integrated Reporting Commission (IIRC) and used in the water sector. The IIRC framework considers the impacts and dependencies of a project on financial, manufactured, intellectual, human, social and natural capital.

A different definition of value is presented in the paper, *The Strategy That Will Fix Health Care* (Porter & Lee, 2013) where the authors propose that in the healthcare sector, value is about achieving best outcomes at the lowest cost – maximising value for patients. This involves moving from a supply driven health care system to one organised around what patients need and moving the focus from 'volume and profitability of services provided' to 'patient outcomes achieved'. Outcomes are considered in terms of the things that matter to patients, and the costs as being those required to deliver the outcomes. This can be considered to provide a more tangible definition than the six capitals which is a broader interpretation aimed at capturing the value of an organisation rather than the value provided to the key recipients.

2.1 Other value considerations

Any value case should always consider the 'do nothing' case which for infrastructure translates to maintaining current levels of service as the baseline. The case for including smart solutions should consider

whether they will improve or degrade the baseline and if there are alternatives to smart solutions that will bring greater value.

Value creation and value capture are two related but distinct processes that depend on the ability to innovate and leverage digital technologies. Importantly, any actions or decisions made by government at any level in relation to infrastructure should demonstrate how they are consistent with the UN Sustainable Development Goals (SDGs) as well as domestic policy such as HMT's Green Book.

2.2 The role of data in realising value from smart infrastructure

Data on its own does not bring value. There is a variety of things that stakeholders can achieve using data such as automation, reduction in costs and avoidance of disruption, but the value is in the outcomes that the data is contributing to. A sociotechnical approach focusing on collaboration, integration and human factors is required to realise societal, environmental and/or economic outcomes through smart solutions: people enact business processes by making use of data acquired and processed through technology. It is the effective exploitation of all aspects in synchronisation, not just the data, that realises the value. The wider the exploitation and scale of a smart solution, the greater the value enabled.

2.3 Valuing infrastructure data and information as an asset in its own right

Although data does not bring value on its own, properly curated high-quality data which has a line of sight to desired outcomes is valuable as it enables better decisions. The Gartner Infonomics Model (Laney, 2017) an organisational approach proposed by technology research and consulting firm Gartner, supports the valuation of information by treating it as an actual asset and provides organisations a foundation and methods for quantifying information asset value (Figure 1).

The Gartner Infonomics Model includes indirect or internal measures which are focused on improving information management and tracking the progress and impact of data management initiatives. These internal value generation measures are typically applicable where the emphasis is on identifying and targeting opportunities to further improve the current business operating model by improving the effectiveness or efficiency of extant business processes without fundamentally altering the core business proposition.

External or direct infonomics measures are used where business value generation can be measured clearly and explicitly in financial terms, such as when the data itself is sold or traded as an information product or service, or is otherwise directly attributable to improving the success of the business model.
Negative impacts and liabilities can affect an organisation financially in different ways. They may arise from such factors as poor data quality, system failures, data loss, data security breaches, privacy enforcement, noncompliance or even accidental processing incidents. Collecting and storing data but then poorly curating the data so that it is not interoperable, and cannot be used effectively over a long period of time, or outside the organisation which generated it, results in a loss in value of/from the data and is a missed opportunity. Organisations that fail to measure and manage information fail to generate sufficient value from it.
It should be noted that the Gartner Model, while very useful, does not incorporate indirect/societal benefits. It works from the perspective of a cost/benefit analysis for an individual organisation (or system), and therefore does not account for wider externalities.

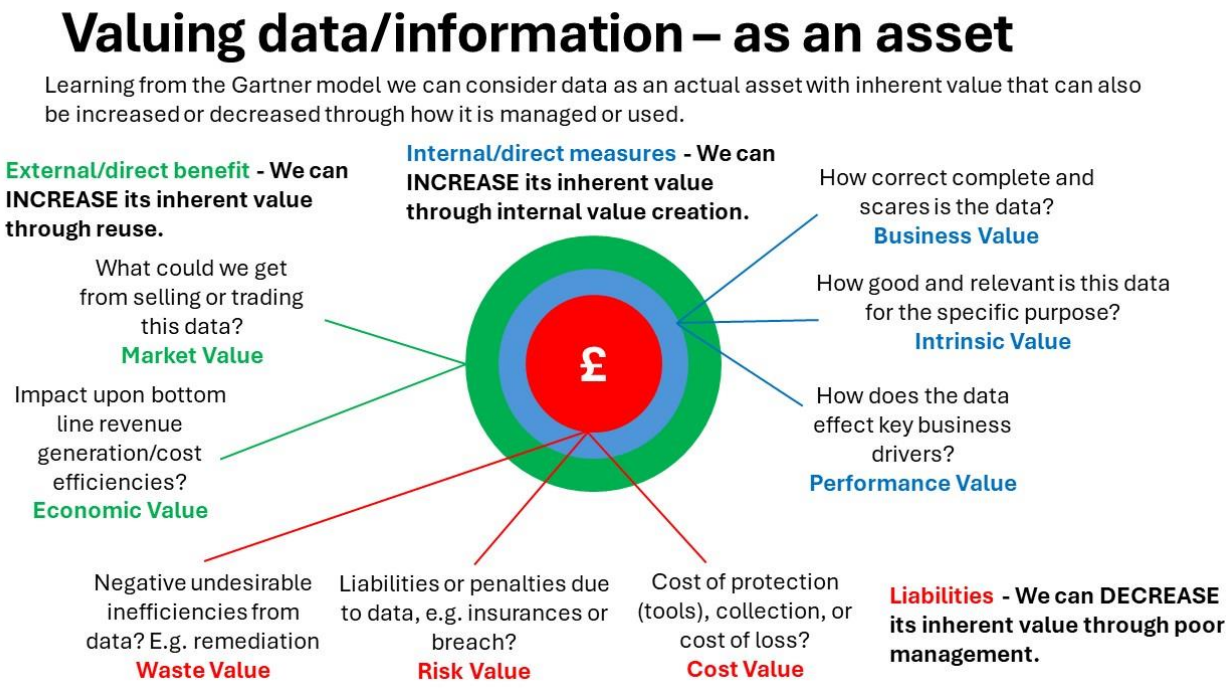

Figure 1. Data valued as an actual asset with inherent value, after Laney (2017)
Credit: Matt Edwards/Anglian Water

National Highways provides a good example of the potential benefits of valuing information as an asset. In the publication, *Information vision and strategy: Connecting ourselves and building trust,* Highways England (2020) describes how by valuing their information, they can better understand their risk, the full value they create, and the full benefits of investment. This enables them to transform a business problem, low data maturity, into a sustainable advantage, which will benefit the organisation's future, its customers and the UK.

2.4. What tangible value does Smart Infrastructure bring?

Smart infrastructure solutions capture data on real performance of actual assets (versus that predicted by modelling), which enables better decisions for design, delivery, operation and maintenance, and renewal of infrastructure assets, networks, and systems. This can be through directly informing decisions, or through enabling calibration and refinement of design and performance models.

Better data and information can improve construction quality by:

- Streamlining processes and sitework enabling project managers to make well-informed decisions quickly and accurately.
- Tracking the flow of materials and resources during a project, ensuring that all necessary resources are available when needed, thereby helping to optimise construction times, reduce waste and minimise potential environmental impact from the project.
- Validating as-constructed quality and performance (e.g. pile and diaphragm wall integrity) and thereby increasing confidence in compliance or improved understanding of behaviour.
- Avoiding the potential risk of rework costs and associated delays.
- Bringing potential benefits in programme, saving time through quicker validation, and improving safety, by reducing exposure to hazards for site workers.

For asset management, better data and information bring benefits including:

- Predictive and planned maintenance instead of reactive interventions (enables intervention at the optimum time before deterioration has had progressed to a point where major intervention is needed).
- A better understanding of risk, enabling a reduction in risk.
- Predictive modelling to assess how the system will perform under various stress factors such as increased extreme weather events due to climate change.
- The opportunity to optimise performance.
- A better understanding of strong and weak points in a system.
- A better service and customer experience.
- Safer operation – preventing accidents due to component failures.
- Carbon and material savings.
- A better understanding of system behaviour.

For infrastructure owners, operators, and managers better data and information can result in direct cost reduction through:

- Continuous monitoring of critical components.
- Reducing high risk situations such as requiring operatives to carry out inspection work in tunnels, on lane closures, or rail possessions.
- Continuous monitoring and better information preventing unnecessary closure of assets and delays to services.
- Providing accurate measurements of asset life used vs life remaining preventing unnecessary intervention or replacement.
- Enabling a predict-and-prevent approach to maintenance to enable intervention and action planning resulting in reduced penalties and cost of disruption.

Through its use to increase knowledge and learning, information derived from smart solutions can move the sector forward by:

- Informing standards.
- Validating and improving models.
- Increasing professional and academic knowledge of infrastructure performance.

3. Maximising the benefits of smart infrastructure

There are a number of avenues to explore when looking at maximising the benefits of smart infrastructure solutions. Those that were considered at the roundtable are discussed below.

3.1 Focus on enabling outcomes

It is only when we shift our focus from creating the built environment to the outcomes enabled by it that people and nature can thrive together for the generations to come. This quote from *Our Vision for the Built Environment* (A collaboration, 2021) clearly describes the importance of focusing on the outcomes infrastructure enables rather than the infrastructure itself. The same is true for smart solutions – it is not the technology but how that technology/solution will contribute to and enable the desired outcomes. Using an IOO (Inputs, Outputs, Outcomes) logic model approach such as the Kellogg Logic Model will keep a focus on enabling outcomes.

However, we often find that functional specifications include a lot of detail on the physical asset but little on the digital asset. This is often due to a lack of clarity and understanding from the owner/operator about

their information requirements and what is needed to enable the outcomes they want. The majority of the value enabled by infrastructure is ultimately in the operation not the delivery. If the operator does not specify and receive what they need, they may not be able to fully realise the value of either the data or the physical asset. Early planning of the handover from construction into operation is key to driving that value. Asset owners and operators and other key stakeholders need a clear understanding of the practical aspects of use, maintenance, durability and issues around resilience and potential obsolescence (when the physical asset and the digital asset have different life cycles) and this needs to be shared with the delivery team during the design and construction process. Infrastructure owners/operators need to be clear that a monitoring solution is providing the data and information required, and evidence from the technology provider that monitoring technology is working as specified. In reality, there is an element of push and pull to achieve this and a requirement to collaboratively build the skills and capacity that are needed to be creative in this space within organisations.

3.2 Learning from other sectors

There are lessons to be learned from sectors whose use of smart solutions and data sharing is more mature than in infrastructure and construction. The aviation industry collects a plethora of data to manage the whole life cost of their assets and to know their risk profiles. While they can be fierce commercial competitors, airlines share information to improve the safety and performance of their sector. In particular, the sharing of safety data has played a critical role in the continuous improvements in airline safety with information anonymised to manage any reputational risks. The oil and gas industry are likewise mature, with monitoring used to understand the real-time condition and performance of their assets. Both sectors have a low-risk appetite as the impact of failure is high – particularly safety, financial and reputational impacts.

The UK Building Safety Act 2022, produced in the wake of the Grenfell Tower disaster, aims to ensure that high-rise buildings are designed, constructed, and managed to be safe for occupants. It promotes transparency by requiring building owners to share information about the safety of their buildings and any safety measures in place. A 'golden thread' is required which involves keeping a digital record of crucial building information – starting from the design phase and continuing throughout the building's life cycle. A building's information must be, kept digitally, kept securely, a building's single source of truth, available to people who need the information to do a job, available when the person needs the information and presented in a way that person can use.

'What if?' scenarios and the value of the counter factual

There is a lot a lot to be learned from the insurance sector. Their business is based on what will be the cost if something goes wrong, who is affected and who is liable. Asking the 'What if?' questions enables an understanding of all possible risks and the value of understanding them. The infrastructure sector needs to be a bit more comfortable with using metrics on the 'What if?' side and consider them as valuable and be comfortable using 'What if?' when costing. A part of the value of smart solutions is measured by the negative impact of their absence.

3.3 Policy and regulation as an enabler

Regulation has a role in pushing the boundary to inspire a different style of solution. However, regulation should not be an immediate reaction. Careful thought is required to ensure that regulation is a positive enabler for change rather than an unintended obstacle.

UK BIM Mandate

An analogous example of how forward-looking policy can facilitate the adoption of digital technologies is provided by the UK BIM mandate. Whilst not a regulation, the Mandate, set out in the UK Government

Construction Strategy in May 2011, required infrastructure and construction projects procured by central government departments, agencies and non-departmental public bodies to use fully collaborative 3D BIM (BIM Level 2) as a minimum by April 2016. In 2019, the BIM Mandate was updated, to require adoption of the new ISO 19650 standard for BIM. The BIM Mandate has been reinforced by all subsequent strategic government publications for infrastructure, including the Construction Playbook and the Infrastructure and Project's Authority's *Transforming Infrastructure Performance (TIP) Roadmap to 2030* (IPA, 2021). As a result of the BIM Mandate, the UK is considered a global leader in the adoption of BIM.

Regulation for system wide issues

There is a need for regulation around system-wide issues outside the boundaries of a single organisation such as safety, net zero etc. The National Infrastructure Commission in its *Second National Infrastructure Assessment* (NIC, 2023) recommends that there is a role for government in setting outcome based resilience standards for infrastructure sectors as a way to align cross sector action on resilience. Setting that expectation of coordination as a direction is imperative to achieving a resilient infrastructure system to support the UK's economy and wellbeing.

Levers resulting from new regulation

As mentioned above, the Building Safety Act 'golden thread' reporting requires that digital information should be effectively stored, managed, and available throughout the life cycle of a building. Although this is only legally applicable to a relatively small subset of high-risk buildings, it may effectively extend to other building projects when insurers, finances and others understand the benefit of this approach to information management and the quality of information that is provided. This will encourage a wider conversation around the most effective ways to gather and maintain the required data and the advantages of smart solutions, particularly the potential for risk reduction.

Another lever for regulators is stipulating a minimum data quality. MOSL, the market operator for the non-household water retail market in England, has driven data quality performance as a surrogate for regulatory performance. This has had a big impact on the adoption of smart solutions because if you want to measure data quality, you actually have to opt in to smart solutions.

3.4 Building trust in the benefits of Smart Infrastructure

Issues around smart technology adoption were discussed in detail in the report, *The Role of Funding, Financing, and Emerging Technologies in Delivering Infrastructure fit for the 21st Century*. (Schooling et. al., 2023). The chapter on emerging technologies covers themes around barriers to adoption, technology adoption cycles for infrastructure systems, and managing expectations of technologies. The report states that, "Unless we create a large market for smart infrastructure, it will be difficult to adopt emerging technologies in our everyday practice. It is thus important first to build trust with infrastructure owners and community members and develop a dialogue defined by shared values. We must then demonstrate the value and maturity of emerging technological applications, and organisational readiness for their adoption". (See the full list of report recommendations related to emerging technology in the appendix to this paper.)

Case studies are needed to show what is possible and to bring opportunities to drive forward the benefits of smart solutions. Value can be communicated through effective storytelling that illustrates the return on investment and the cost avoidance of different options.

Some organisations are developing 'asset data/information strategic road maps' to understand what they need the data for and how it connects to their business needs. It would be useful to create a timeline infographic of the value of data across the lifecycle of an asset to understand who gets value at various stages and how the type of value changes across the stages.

4. What is holding back acceptance and deployment of smart infrastructure solutions?

4.1 Economies of scale

A key issue in take up of smart infrastructure solutions for some infrastructure clients is the number, geographical spread and diversity of their assets and the huge range of potential failure modes. There are examples of successful pilot projects where smart solutions provided key information on understanding the performance of an infrastructure asset. However, scale up to similar assets has often proven not to be technically and/or economically viable. However, there are examples of successful scale up. In rail, for example, ultrasonic failure detection and Plain Line Pattern Recognition (PLPR) have contributed to an order of magnitude reduction in the number of broken rails (around 1,000 to 100 per year). Crucially, these implementations were successful because sensors could be fitted to monitoring trains and because track configurations are similar across the whole network. There are other good examples in other rail asset types but the heterogeneity of signalling, electrification, bridges, stations etc. doesn't provide the economy of scale needed to scale up from pilot applications.

Instead of focusing on technology scale up, the approach/process for deciding on which assets/systems need to have enhanced monitoring can be scaled up. Assets that either pose significant safety risk and/or disruption to service (be that transport, power, water etc.) can be identified and prioritised to help prevent fatal accidents such as the Stonehaven derailment as well as near misses such as the wing wall collapse at the Plessey Viaduct on the East Coast Mainline. A more mature and realistic assessment of risk to life and to service, and the wider economic costs of disruption and reputational damage, would make the case for a more consistent approach to assessing the need for monitoring and then investing in it.

4.2 Firefighting and short termism

In comparison to other sectors such as aerospace and oil and gas, infrastructure clients can be seen as behind in terms of adoption of smart infrastructure. The reasons for this include a lack of capability to utilise these technologies within organisations, being consumed with firefighting, perceived cost, and risk aversion. Some clients are caught up in a cycle of firefighting through short term funding cycles – responding to failures in aging assets in sub optimal (and often higher carbon) ways due to the urgency required by the regulator and the fear of not hitting targets. They are having to manage an asset to keep it safe and functional with little capacity to innovate. This short-termism gets in the way of pursuing long-term whole-life-value solutions and does not look set to change in the near future. This is obviously a problem when the sector is facing calls for radical transformation to respond to the climate crisis and other systemic problems.

How do you demonstrate the value of adopting smart infrastructure to support long term outcomes when an organisation is subject to short term funding cycles? With a short-term horizon, this is a challenge because a business case can be made on the whole life cost, but decisions are being made as to what is affordable within the short (e.g. 5-year) funding cycle. Longer term planning conversations with government happen in relation to the larger infrastructure investments. What are the mechanisms to discuss whole life value within a short-term cycle?

There is a perception that a focus on capex instead of opex has resulted in sustained underinvestment in asset management leaving the infrastructure sector in a period of managed decline. Treating maintenance and asset management spend as CapEx instead of OpEx – as it is investment in keeping a capital asset in operational condition – would help to address this.

4.3 Not taking a system-of-systems approach to regulation

Overall, there is a need for more of a joined-up view because of the interdependence of our infrastructure systems. National infrastructure strategies must address the whole system, existing infrastructure as well as

new. To get more from what we already have, as well as from what we will build, we must address the connections and interdependencies between sectors (CSIC and CDBB, 2020).
ICT and energy are mutually interdependent systems. We can't have transport systems and water systems without energy and ICT. Interconnections and interdependencies also exist between economic and social infrastructure and the natural environment include ecosystem services, flood alleviation, recreation, resources and waste disposal. These systems rely on each other, but they are in regulatory silos. The answer is not necessarily more regulation but rather better, more joined-up regulation.

4.4 Lack of cross sector collaboration

Innovation through collaboration across sectors and scales, with local and central government, the public and other stakeholders is key to responding to systemic problems such as environmental sustainability, climate change, the biodiversity crisis and achieving net zero. However, the Infrastructure Client Group's (ICG) 2024 *Data and Digital Benchmarking Report* highlights a lack of regular collaboration within and across businesses. With only 6% of survey respondents replying that 'their organisation "always" shares and seeks lessons learnt with other similar organisations'.
A positive example of a collaboration between utilities networks, academia and government, including Anglian Water, BT and UK Power Networks and others, the Climate Resilience Demonstrator Project (CReDo), shows the advantages of combining data and learning across sectoral and organisational boundaries. CReDo is a digital twin project demonstrating how connected data can improve climate adaptation and resilience across a system of systems. Looking at the impact of flooding on the partners respective energy, water and telecoms networks, CReDo demonstrates how infrastructure clients can use secure, resilient, information sharing across sector boundaries to mitigate the effect of flooding on network performance and service delivery. CReDo shows how collaboration through connected digital twins is key to tackling systemic problems like climate change.

4.5 Not sharing learning from failures

Sharing learning, especially the learning from failures is important in preventing such failures from happening again. However useful this would be, it is far from a routine practice. Inevitably organisations are very protective of reputational damage and concerned about liability. A way to tackle this to improve safety is in anonymising reporting, enabling information to be freely shared. This builds on what is done in the airline industry, creating an information system that includes negatives as well as the positives.
Unfortunately, this only exists in niches in our sector. The Rail Accident Investigation Branch (RAIB) publishes reports which describe what happened in an accident in a non-contentious way. RAIB provide learning points with no finger pointing but a clear explanation of what happened and the underlying causes. Another example of sharing of information on things that have gone wrong or nearly gone wrong is the Collaborative Reporting for Safer Structures UK (CROSS-UK). CROSS is a confidential reporting system which allows professionals working in the built environment to report on fire and structural safety issues. These are then published anonymously to share lessons learned and improve safety.

How can we incentivise organisations to share their failures in order to build a data set of how things can go wrong? This can then better inform our smart infrastructure solutions by having a clearer view of desired outcomes (or outcomes to avoid).

4.6 Backward looking culture

A backward looking culture, 'doing it the way we did last time', stifles innovation and may lead to suboptimal decisions. Instead, looking ahead and asking, 'how could we do it better this time?,' with a spirit of continuous improvement, will open new opportunities. This backward-looking culture is driven by a number of factors such as liability concerns and conservatism, but a bigger issue may be around the structure of the sector, with new teams being set up for each project, making it hard to carry learnings from

one project to the next. A more stable supply chain which moves between similar projects would be more effective in innovating. Looking back may lock in ways of thinking that are not appropriate in the current context. Similar to value, decisions and rationale are dynamic. Knowing the rationale but considering the current context enables more informed decisions as contexts change.

While being mindful of avoiding looking back, good practice could be codified in terms of ontologies, data architectures or technology suites that you can plug together, to avoid reinventing the wheel with every project. This would enable the transfer of understanding from one project to the entire industry, facilitating a 'smart from the start' approach. This can then help reduce costs and address the skills gap because we are starting to repeat the same processes. However, when it comes to planning and ontologies etc., there needs to be a balance between passing on lessons and structures from before to facilitate smart solutions and the importance of having the space and culture for experimentation and creativity.

4.7 Disillusionment with tech and not trusting data, lack of visibility of successful use cases

Infrastructure client boards can be wary of smart solutions as they are viewed as IT projects rather than organisational transformation programmes and, due to several high-profile examples of IT projects going wrong over the years, such projects are considered risky. The hype over the Internet of Things (IoT) has not helped. A huge amount of money has been spent across Europe on IoT but there is a perception that it has not delivered bringing a distrust in digital technology. The reasons for this perception may be that the hype was too much and IoT, while valuable, is not the solution it was heralded to be. Much was promised and the costs mounted, and organisations had not really thought through the output – how IOT will improve performance.

Consideration needs to be given to how smart infrastructure can be demystified. In civil engineering/construction it's only since recent large projects like Crossrail that monitoring of infrastructure has been embraced by industry. Although some monitoring solutions are now well developed, operatives are still sceptical of the data because it is frequently not clear to them how it will be used or what the value is. Without this clear purpose, data is considered ‘nice to have’ but not essential. There are scars from a period where acquiring data from sites was very difficult and acquiring high-quality trustworthy information could not be relied on. This brings us back to the need for case studies and clear narratives of the value of smart solutions as well as aligning all stakeholders on the value case for the smart solutions they are using.

5. Smart infrastructure solutions enable a system of systems approach to the built environment

There is increasing discussion in the sector around understanding the interconnectivity and the interdependencies of our infrastructure systems and the value of taking a system-of-systems approach to the whole life of the built environment, including use operation, maintenance, design, delivery, integration, and renewal. Smart infrastructure plays a key role in enabling this system-of-systems approach by providing the data and information required to better understand the performance of infrastructure assets and systems. However, as an industry we struggle to understand how to engage usefully with a system-of-systems approach and, as mentioned earlier, many of our organisations, institutions, processes, and regulations exist in silos making a shared understanding difficult, if not impossible. Current governance models and siloed regulation inhibit the collaboration that is essential for infrastructure owners to work together in an interconnected and interdependent system-of-systems approach. A huge step change is required that begins with collaboration to invent and define new governance and regulations models that can manage complexity. Consideration could be given to how to most effectively develop the required capability, skills and collaboration both within and among organisations. Just as a common language and clear narrative are needed for understanding the value of smart infrastructure, the same is true for understanding and gaining the greatest value from system-of-systems.

In the paper, Flourishing Systems (CSIC and CDBB, 2020), 'system' and 'system of systems' are defined as follows. *"A system is a connected collection of interrelated and interdependent parts; a complex whole that may be more than the sum of its parts. A system is influenced by its environment, defined by its structure and purpose, and expressed through its function. Infrastructure is the interconnected 'system of systems' that provides the physical foundation for our society. It does more than just provide water, power or transport services; it helps to make cities liveable, boosts quality of life and supports productivity and prosperity, all in the context of its interface with the natural environment*." The paper includes a call for "a paradigm shift" where we recognise infrastructure as a system of systems and manage it accordingly.

How do we achieve this paradigm shift? One suggestion is to head towards a PAS (publicly available specification) for understanding system-of-systems in infrastructure. This could follow the model of the development of PAS 2080 which began with the Infrastructure Carbon Review. Perhaps an 'Infrastructure Systems Performance Review' is needed to understand how our infrastructure as a system-of-systems performs and the impact of interventions on the system. A first step towards facilitating this 'paradigm shift' can be development of a 'shared understanding' paper for industry, which would not only provide a shared language to address the issues, but also help to build a consensus for tangible action. The intent would be to collaborate with other key groups that recognise the same need and thereby to build strong industry support.

6. What actions/changes are needed to achieve widespread adoption of SI solutions?

Recommendations for industry and policy makers related to people (skills and culture), policy, data and technology are listed in the table below with the main focus of each recommendation shown with a coloured box.

	Recommendations across People (P), Process (Pr), Data (D), Technology (T)	P	Pr	D	T
1	Develop a 'shared understanding' of how systems-thinking applies to the built environment. Identify how to promote systems-thinking and collaboration across the industry.				
2	Explore where joined-up regulation can address system-wide issues and help smart solutions to realise better outcomes.				
3	Create a common framework for valuation of outcomes. This framework should apply across all national infrastructure when implementing smart solutions.				
4	Develop a suite of value case studies that demonstrate the benefits of smart solutions. This should include a consistent approach to benefit realisation.				
5	Create a timeline infographic of the value of data across the asset lifecycle. showing who gets value at various stages and how type of value changes across the stages and for different types of clients. This should show the different ways that clients and users realise value.				
6	Develop a common data standard for data sharing and collaboration across the industry. Work with existing projects such as CReDo, NDTP, and the Information Management Mandate.				
7	Consider codifying good practice to avoid reinventing the wheel with every project. Investigate how ontologies, data architectures and platforms can drive interoperability.				
8	Establish requirements for smart infrastructure solutions in design, construction, and asset management. This should articulate the benefits that smart solutions bring across the asset life cycle.				
9	Consider the impact of extended regulation periods on infrastructure clients. How do these affect the uptake of smart infrastructure solutions, and how do we avoid the pitfalls of short-term cycles.				
10	Work towards procurement standards for smart infrastructure in public works projects.				
11	Provide an anonymous platform where stories of failures can be shared to inform future initiatives.				
12	Consider the best ways to fill the skills and competency gap in data-centric approaches and smart infrastructure solutions (e.g. developing a data academy).				

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Appendix A

Recommendation from the Emerging Technologies chapter of the 2023 report, *The Role of Funding, Financing, and Emerging Technologies in Delivering Infrastructure fit for the 21st Century.*

Emerging Technologies Recommendation (ETR) 1: Intelligent sensor and autonomy systems must be designed for long lifespans or be adaptable for replacement.

ETR2: Autonomy in infrastructure construction and operation should be developed within the framework of a common data environment (CDE) with standardized data so that efficiencies in infrastructure systems can be achieved.

ETR3: Using the framework of sociotechnical digital twin, infrastructure asset modelling should be linked to social behavior to understand human interaction with physical infrastructure systems.

ETR4: There is a need for machine learning and artificial intelligence to address prediction accuracy and prediction reliability of infrastructure system performance.

ETR5: Through innovations in materials and construction/maintenance processes, future infrastructure systems must be designed to generate their energy or rely exclusively on renewable energy, realizing a net-zero or negative carbon system.

ETR6: There is a need to develop a commonly shared approach to evaluate emerging technology contributions for improved delivery, resilience, net zero carbon, and equity objectives of infrastructure systems. The framework needs to be used to enhance communication between infrastructure owners and technology developers.

Appendix B

Making Smart Infrastructure Business as Usual

10.00 – 16.00 2 February 2024
Mott MacDonald, 10 Fleet Place, London

Participant List

NAME	ORGANISATION
Keith Bowers	COWI
Luke Coomber	Mott MacDonald
Sharon Duffy	Thames Water
George Economides	Department for Transport
Matt Edwards	Anglian Water
Dee Dee Frawley	CSIC, University of Cambridge
Jeannine Gavaghan	Ministry of Justice
Colin George	National Highways
Barry Gibbs	WTW
Neil Gunn	WTW
Fergus Harradence	Department of Business and Trade
Peter Hewitt	Laing O'Rourke
Wendy Ivess-Mash	Defence Infrastructure Organisation
Jim Johnson	Arup
Urszula Kanturska	Sizewell C
Matt Kirk	Anglian Water
Andy Kirwan	Network Rail
Nirmal Kotecha	UK Power Networks
Mike Laws	AECOM
Richard Lennard	Sellafield Ltd
Chrysoula Litina	National Highways
Carmen Muriana Cobo	Transport for London
Ajith Parlikad	CSIC, University of Cambridge
Fraser Perceval	Jacobs/CSIC ECAPP
Robert Percy	COWI
Alan Proctor	Environment Agency
Jennifer Schooling	CSIC, University of Cambridge
Brian Sheil	CSIC, University of Cambridge
John St Leger	HS2
Clara Wikforss	National Infrastructure Commission
Melissa Zanocco	Infrastructure Client Group

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