Civil engineering insights into digitally retrofitting infrastructure assets and networks

About digital retrofit

By 2050 the UK population is expected to number about 77 million[1] with the economy worth up to £3.7 trillion.[2] Much of the UK population's need for transport, energy, water supply, wastewater and flood defence services will need to be met by infrastructure that exists today and has done for many years. For example, the majority of the existing rail network was established by 1870[3] and 70% of UK dams within the scope of the Reservoirs Act 1975 were built before 1900.[4]

Boosting productivity, economic growth and creating new routes to market, through improved physical and digital connectivity, will rely on upgrading these existing infrastructure assets and networks both physically and, importantly, digitally. Digitally retrofitting older infrastructure assets can offer improvements to design, maintenance, reliability and user experience, while extending the useful life of structures. Investment in new and replacement infrastructure will continue to be necessary, but meeting and sustaining future need will require the infrastructure we have today to continue to work well, if not better. This makes financial sense as it can avoid large new capital investments, while also helping to minimise the disruption and environmental impacts, including carbon emissions, associated with new construction.

While there are ambitious plans to digitalise and automate some infrastructure networks,[5] digital retrofitting need not always be complicated or costly. The installation of sensors to detect changes in a structure and the deployment of drones can help to minimise the costs of maintenance and repair, and ensure issues are noticed and addressed more quickly.

Purpose of this paper

This paper provides insight into the potential benefits of digitally retrofitting infrastructure assets and networks, examining challenges to doing so and drawing on lessons from existing examples of digital retrofit. It has been developed through discussions with ICE Fellows, a round table of senior sector stakeholders and available published evidence.

The potential benefits of digital retrofitting

Cost and environmental efficiencies

Digitalisation is increasingly central to the delivery of infrastructure and improving asset performance. The take-up of digital processes and technology within the infrastructure sector itself, however, lags behind other key sectors of the economy. In 2017, just 7.7% of construction businesses within the EU 28 had a high or very high Digital Intensity Index (the 'availability at firm level of 12 different digital technologies') against an average of 20% across all EU businesses.[6] There is evidence to suggest that the cost of infrastructure maintenance in the UK is higher compared to other countries, with a study on track maintenance suggesting a weighted average cost for metro systems that is 46% higher in the UK.[7]

[1] Eurostat, ONS (2017) Overview of the UK Population: March 2017
[2] ICE (2016) National Needs Assessment
[3] Government Office for Science (2018) The History of Transport Systems in the UK
[4] ICE (2015) A Guide to the Reservoirs Act 1975
[5] Network Rail (2020) Digital Railway
[6] European Commission (2018) Integration of Digital Technology
[7] HM Treasury, Infrastructure UK (2010) Infrastructure Cost Review

Institution of Civil Engineers is a Registered Charity in England & Wales (no 210252) and Scotland (SC038629)

Maintaining an infrastructure asset over its life cycle often costs more, in economic and environmental terms, than the initial capital investment. Improved decision-making through the availability of consistent, quality data is one of the most potent ways that digitalisation can unlock value. Normalising the automated collection and storage of data that is accessible from anywhere, on multiple platforms and devices, creates considerable time and cost savings when compared to more traditional methods of data collection, storage, access and maintenance management. This is best facilitated through a common approach to data modelling, allowing interoperability so that separate databases can interact with one another.

The demand-side benefits of digitally retrofitted assets can be significant, notably on energy efficiency – a 2017 report by the American Council for an Energy-Efficient Economy estimated a reduction in energy consumption of 18% in offices, 14% in shops and 8% in hospitals using retrofitted smart technologies.[8] Such an approach could cut heating and ventilation costs by as much as 40%.

Extending asset life cycles

Digitally retrofitting infrastructure provides a route to prolonging an asset's life cycle by boosting resilience, creating improved conditions for asset users and improving efficiency.[9] This approach can be maximised through predictive maintenance, where sensors provide real-time data about condition and performance, optimising asset maintenance.[10]

There are examples of software environments which enable assets to schedule their own repairs based on sensor-gathered data, with Boeing implementing such a system in 2011.[11] Balfour Beatty sets out a possible future in its 2017 report *Innovation 2050*, outlining that the Internet of Things will be able to power smart buildings in smart cities, with assets able to order their own replacement parts as necessary.[12]

What needs to be done to enable digital retrofitting?

Digital skills and training

An ICE member survey as part of a skills review in 2018 identified that the development and adoption of digital technology was perceived as the main trend that will have an impact on skills.[13] In order to deliver digital retrofitting of assets, upskilling of the existing workforce is required. There is an acute skills deficit in the wider economy when it comes to digital skills and roles related to STEM subjects.[14] Estimates suggest that by 2030 five million workers could become acutely under-skilled in basic digital skills, with up to two-thirds of the workforce facing some level of under-skilling.[15] The more infrastructure assets generate and rely on data, the greater the need will become for all elements of the workforce invested in the design, construction, operation and decommissioning of infrastructure to become more digitally literate.

Cyber security

In the UK in 2017, 590 significant cyber incidents were reported to the National Cyber Security Centre (NCSC), including foreign-state attacks on UK telecommunication and energy infrastructure.[16] According to the German Bundesamt für Sicherheit in der Informationstechnik (BSI – Federal Office for Information Security), in Germany during 2018 there were around 114 million new malware programs and over 110,000 bot infections each day, aimed mostly at mobile devices or

[8] American Council for an Energy-Efficient Economy (2017) Smart Buildings: A Deeper Dive into Market Segments
[9] ICE (2017) State of the Nation 2017: Digital Transformation
[10] ICE (2018) AI, Machine Learning and Data Science: Shaping the Future of Existing Infrastructure
[11] ICE (2018) ICE Guidance Paper: Intelligent Assets for Tomorrow's Infrastructure
[12] Balfour Beatty (2017) Innovation 2050: A Digital Future for the Infrastructure Industry
[13] ICE (2018) ICE Professional Skills
[14] Industrial Strategy Council (2020) Annual Report
[15] Industrial Strategy Council (2019) UK Skills Mismatch in 2030
[16] National Cyber Security Centre 2017 Annual Review

Institution of Civil Engineers is a Registered Charity in England & Wales (no 210252) and Scotland (SC038629)

devices on the Internet of Things (IoT).[17] Of these there were 145 reports relating to critical infrastructure, with 55 affecting the transport, energy and water sectors, which had the potential to create supply bottlenecks or disruption to public security.[18]

Widescale digital retrofitting of infrastructure assets and networks can create new vulnerabilities. Assets and systems that are retrofitted with technology such as smart sensors and communication packages to take full advantage of the IoT may bring numerous efficiencies and lead to better decision-making, but between 2015 and 2018, 20% of organisations observed at least one IoT-based attack.[19]

Asset owners and their supply chains have increasingly turned paper processes into digital ones, handling vast amounts of data in the operation of critical infrastructure.[20] Protecting these systems and data against malicious actions is vital as a line of defence against failure. This is well understood in government, which established the National Cyber Crime Unit in 2015, recognising the potential for hostile actors to attack infrastructure with the aim of doing harm to the economy or individuals.[21] The Department for Transport, mindful of the risks of a cyber-security breach in the rail sector, has issued guidance on the safe and secure operation of electronic and software-driven systems in use on the network.[22]

The digital twin

The rise of digital design applications has led to the concept of the digital twin, a representation of a physical infrastructure asset in a digital format which can aid the modelling and understanding of that asset. This concept is particularly important with regards to digitally retrofitting existing assets, as it enables asset and network owners to understand where a system could benefit from improvements, allowing for value to be unlocked in new ways and helping to re-prioritise asset management.[23] The concept of a national digital twin – an ecosystem of digital twins connected via securely shared data – and an information management framework, which would enable effective information sharing, is an extension of this idea.[24]

Values to inform this approach have been proposed in *The Gemini Principles*, published by the Centre for Digital Built Britain.[25] These are nine principles relating to three general areas – purpose, trust and function – designed to guide the development of the framework and the national digital twin.[26] These principles include the need to be open, ensuring security, being adaptive to evolution and enabling value creation.

Interoperability and common standards

Increasing the digitalisation of existing economic infrastructure, facilitated in part through the roll-out of a full-fibre broadband network, will enable new methods of working and insights not only within, but also between, assets and networks.[27] Connecting infrastructure assets and networks and greater data sharing could release an additional £15 billion per year of benefits across the UK infrastructure sectors.[28]

Perhaps the biggest barrier to achieving this data sharing is the lack of interoperable data. A lack of quality data and of consistency of data impedes the improvement of models for predicting project estimates[29] and a lack of interoperability between information systems means firms expend considerable time and resources when moving between and within

[17] Bundesamt für Sicherheit in der Informationstechnik (2019) Report on the State of IT Security in Germany 2019
[18] Bundesamt für Sicherheit in der Informationstechnik (2018) The State of IT Security in Germany 2018
[19] Gartner (2018) Gartner Says Worldwide IoT Security Spending Will Reach $1.5 Billion in 2018
[20] ICE (2018) In Plain Sight: Assuring the Whole-Life Safety of Infrastructure
[21] Ibid
[22] Department for Transport (2016) Rail Cyber Security: Guidance to Industry
[23] ICE (2017) What is a Digital Twin?
[24] University of Cambridge (2019) Gemini Principles
[25] Centre for Digital Built Britain (2018) The Gemini Principles
[26] University of Cambridge (2019) Gemini Principles
[27] ICE (2020) Civil Engineering Insights on the Roll-Out of Full-Fibre Broadband and Alternative Proposals
[28] Deloitte (2017) New Technologies Case Study: Data Sharing in Infrastructure
[29] ICE (2019) Reducing the Gap between Cost Estimates and Outturns for Major Infrastructure Projects and Programmes

Institution of Civil Engineers is a Registered Charity in England & Wales (no 210252) and Scotland (SC038629)

projects.[30] In order for large-scale projects like the national digital twin to operate, interoperable software and data standards are necessary. Interoperability is a core tenet of the Gemini Principles.[31]

Common standards would be useful for the wider industry to enable this. Many infrastructure sectors are set up to encourage competition, particularly in energy and rail, which can lead to fragmentation. At the same time, interdependencies, where one asset or sector relies on another, are becoming more prevalent. A future Connected and Autonomous Vehicle (CAV) sector will depend on an expanded, or smarter, energy grid and telecommunications sector. Technologies like floating solar panels, which reduce the evaporation of water in reservoirs, mean some infrastructure owners can operate in more than one sector.[32]

For example, a new asset may increase demand on the existing electrical supply network. With an independent digital twin, this could be predicted and permitted for in future maintenance costs by that single asset owner, but connected digital twins could allow the data to be simultaneously communicated to district network operators to work out predicted demand for similar existing assets. This data can ultimately influence decision-making and lead to improvements in efficiency and performance on a systems basis.

Public sentiment around digitally enabled infrastructure

The widescale adoption of embedded sensors, automated tracking of passengers on transport networks or real-time monitoring of the use of energy and water will inevitably raise concerns from the public about the extent to which their lives are being monitored and what that data is used for.

The UK public are wary of giving away too much information about themselves, with 80% saying that they try to limit the amount of personal information they either put online or share with companies, and 85% stating they would boycott a company that repeatedly showed disregard for protecting consumer data.[33]

ICE's 2019 policy paper on 'pay as you go' roads funding found that, with regards to the potential for car location data being tracked and shared, as long as appropriate privacy safeguards and oversight is in place, the public will likely come to accept a new system.[34] This is particularly true if the data is managed by a trusted organisation or intermediary, with public confidence maintained through regulation, privacy laws, anonymisation of data and transparency on what the data is used for.

While the public are keen to limit the data they share, a 2016 poll by Populus on smart meters found that 83% of those with a smart meter believed their energy bill was accurate, compared to 65% of those without a smart meter.[35] A similar pattern exists regarding other criteria – people with a smart meter were more likely to trust their energy supplier and better understand their bill than those without.[36]

However, digital retrofitting of existing assets has not always had wide acceptance. On smart motorways in the UK, public acceptability has been low: 68% of drivers believe removing hard shoulders on motorways compromises safety,[37] while only half of drivers who have driven on an 'all-lane running' motorway say they would know what to do if they broke down and were unable to reach a refuge area.[38] Concerns over safety prompted a government review in 2020, with plans to abolish dynamic hard shoulders and speed up the deployment of technology to detect stopped vehicles.[39]

[30] ICE (2017) State of the Nation 2017: Digital Transformation
[31] Centre for Digital Built Britain (2018) The Gemini Principles
[32] United Utilities (2018) Floating Solar Farm Gets Underway at Lancaster Reservoir
[33] YouGov (2018) 72% of Brits Haven't Heard about GDPR
[34] ICE (2019) Pay As You Go – Achieving Sustainable Roads Funding in England
[35] Populus (2016) Smart Meters: The Verdict
[36] Ibid
[37] RAC (2019) 68% of Drivers Say Removing Hard Shoulders on Motorways Compromises Safety
[38] Ibid
[39] Gov.UK (2020) Strategic Roads Update: Smart Motorways Evidence Stocktake

Institution of Civil Engineers is a Registered Charity in England & Wales (no 210252) and Scotland (SC038629)

Lessons from existing schemes and projects

The Digital Railway programme

Network Rail currently owns 64,000 signalling assets and spends around £800 million each year maintaining and renewing them.[40] At the current rate of replacement and network growth, maintaining these assets nationwide will become unsustainable. In addition, most lines operate at peak capacity, with some services up to 200% oversubscribed, and freight demand increasing by 100% between 2003 and 2017.[41]

The Digital Railway programme is designed to retrofit the UK's existing railways system with digital signalling and communications to address capacity issues, while also realising significant future savings and making the railways cheaper to run.[42]

Adopted technology includes European Train Control Systems, allowing trains to run closer together while maintaining safe distances, systems to improve driver decision-making on performance and safety, active traffic management and new telecoms and data systems.[43] Network Rail is also seeking to improve training to increase the capability and expertise of its workforce, and those of partner organisations, to maximise benefits.[44]

Smart motorways and Connected and Autonomous Vehicles

Smart motorways are a form of active road management designed to increase capacity, smooth traffic flows and allow for individual management of lanes.[45] Around 400 miles of the road network have been converted to a smart motorway format, with motorways having their hard shoulders converted to 'all-lane running' or used on a dynamic basis.[46]

A smart motorway uses technology that monitors traffic levels, changes the speed limit to smooth traffic flow, activates warning signs to alert drivers to hazards and closes lanes for safety or to prioritise emergency traffic.[47] This technology takes the form of vehicle detection systems which provide data on traffic flow and which, in turn, set automated, or semi-automated, traffic messages or speed limit changes.[48]

Connected and Autonomous Vehicles (CAVs) are an as yet unproven concept. However, should their development be successful, a CAV system would require significant retrofitting of existing roads to meet digital standards that can accommodate high bandwidth and always-on communications equipment. The Millbrook testing ground, one of several sites for the testing of CAV technology in the UK, provides a 5G test bed to allow for the testing of connectivity on the basis of the Internet of Things, provided by fibre cables, masts and base stations.[49]

Wind turbine optimisation

The application of digital twins in the wind industry is being used to proactively repair and maintain existing wind turbines.[50] By using data to understand the health condition of a turbine, or fleet of turbines, asset owners are provided with insight into when maintenance is anticipated, enabling maintenance schedules to be optimised and reducing the need for unplanned maintenance to take place. In turn, this leads to cost efficiencies and minimises the amount of time a turbine may be offline.

[40] Digital Railway (2015) More Trains, Better Connections, Greater Reliability
[41] Arcadis (2017) Digital Railway
[42] Ibid
[43] Network Rail (2020) Proven Technology
[44] Ibid
[45] Highways England (2020) Smart Motorways
[46] Highways England (2014) Strategic Business Plan 2015–2020
[47] Highways England (2020) Smart Motorways
[48] ITS UK (2020) Rise of Smart Motorways
[49] Millbrook (2020) Connected and Autonomous Vehicle Testing
[50] Windpower Engineering (2019) How Digital Twins are Transforming Wind Operations

Institution of Civil Engineers is a Registered Charity in England & Wales (no 210252) and Scotland (SC038629)

In addition to improving operation, maintenance and reliability, the digital model can increase annual energy production. By virtually testing the impact on the turbine if wind speed increased or decreased, if it blew for longer, or if there was very little wind at all, engineers are able to make evidence-based decisions such as whether to increase a turbine's power rate to generate more electricity when demand and prices are higher.[51] GE Renewable turbines have experienced increased megawatt-hour output of up to 7%.[52]

International comparators

The concepts of digitally retrofitting infrastructure assets through smart cities and smart grids have gained footing in many areas around the globe.[53]

Barcelona

The city of Barcelona is committed to developing 'CityOS', a city operating system on an open-data platform.[54] Barcelona's city council manages infrastructure based on open-code 'Big Data' technology, which provides better data governance, quality controls and more effective privacy and security.[55] This approach allows the city council to make informed, data-driven decisions.

The city has a network of over 19,000 sensors that transmit three million daily recordings on energy, noise, waste, weather, parking capacity, air quality, water levels and flows of bicycles, pedestrians and vehicles.[56] In the period 2015 to 2019, the city reduced its water use in public parks by 25%,[57] waste collection routes were optimised based on how full municipal bins were, and more than 1,100 LED lampposts were installed which, alongside reducing energy use by 30%, act both as free public Wi-Fi points and monitors for air pollution.[58]

Singapore – Smart Nation initiative

Singapore launched a smart city initiative in 2014 that consists of three key pillars: digital economy, digital society and digital government.[59] The OECD describes the initiative as 'a comprehensive smart city strategy from which other countries can draw lessons', highlighting efforts to teach coding and other digital skills to those of school age or needing to retrain.[60] The strategy is also user focused and inclusive, ensuring resources are produced in multiple languages and placing an emphasis on addressing the challenges associated with an ageing population.[61]

The Government of Singapore has decided to make artificial intelligence the defining issue for the next phase of its strategy.[62] This will focus on areas where Singapore believes it has a historical competitive advantage, such as intelligent transport and logistics. The city state hopes this will enhance its competitiveness, generate economic returns, provide new jobs and upgrade the skills and capabilities of its people. Singapore recognises that, alongside the Smart Nation initiative, there is a need for a set of standards that allow for the data generated between different systems to be interoperable.[63]

[51] GE (2018) The French Connection: Digital Twins from Paris Will Protect Wind Turbines against Battering North Atlantic Gales
[52] Ibid
[53] Amsterdam Institute for Advanced Metropolitan Solutions (2017) Smart Retrofitting of Urban Housing
[54] Grow Smarter (2020) From Dream to Reality: Transforming Cities for a Smart, Sustainable Europe
[55] Ajuntament de Barcelona (2019) Barcelona Digital City: Putting Technology at the Service of People
[56] Ibid
[57] Ibid
[58] Harvard Kennedy School, ASH Center for Democratic Governance and Innovation (2016) How Smart City Barcelona Brought the Internet of Things to Life
[59] OECD (2019) Economic Outlook for Southeast Asia, China and India 2019 – Update
[60] Ibid
[61] Ibid
[62] Smart Nation Singapore (2019) Transforming Singapore Through Technology
[63] NIC (2017) Study on International Best Practices in Using Technology to Improve Productivity

Institution of Civil Engineers is a Registered Charity in England & Wales (no 210252) and Scotland (SC038629)

Alternative approaches

Retrofit or replace?

While retrofitting existing infrastructure to meet new digital standards or to take advantage of new technologies can have numerous benefits, in some circumstances it may be more cost effective to replace ageing infrastructure entirely.

For some assets within an infrastructure network this is inevitable. As the Digital Railway will allow for more intensive use of track, including longer and heavier trains running more closely together, many of the bridges on the rail network, which were designed for the Victorian era and the design requirements of that time, will need to be replaced.[64] Further, while the Digital Railway programme will result in significant new capacity on existing lines, future demand will still necessitate the construction of new infrastructure, which will provide relief to existing lines by replacing some services, moving them to new track.[65]

Segregation, or partial upgrade, of an asset

There will likely be circumstances where new and old technologies coexist, at least for a time, on legacy infrastructure assets. Technology company City Science was joint winner of the National Infrastructure Commission's Roads for the Future competition,[66] presenting a paper on Dedicated Driverless Spaces, which would operate as segregated lanes on existing roads for CAVs in much the same way as bus lanes are used in some cities.[67]

City Science argues this would ensure minimised interaction between driven and driverless vehicles, alleviating concerns about safety and congestion caused by human and AI drivers being unable to anticipate each other in mixed traffic. It would also simplify regulatory legal and technological challenges CAV traffic might face.[68] This approach may become more prevalent in future, enabling some benefits to be accessed earlier, allowing a test bed for further development and providing the option of phased transitions without widescale disruption.

About ICE

Established in 1818 and with over 95,000 members worldwide, the Institution of Civil Engineers exists to deliver insights on infrastructure for societal benefit, using the professional engineering knowledge of our global membership.

For more information please contact:

David Hawkes, Policy Manager, ICE

policy@ice.org.uk

[64] Network Rail (2020) Bridge Replacement
[65] Network Rail (2020) Crossrail 2
[66] National Infrastructure Commission (2018) Competition Winners Pave the Way for Roads for the Future
[67] City Science (2018) Roads for the Future: Dedicated Driverless Spaces
[68] Ibid

Institution of Civil Engineers is a Registered Charity in England & Wales (no 210252) and Scotland (SC038629)