Capability Framework and Research Agenda for a Digital Built Britain

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Key to supporting materials

The following reports and notes do not necessarily reflect the views of CDBB and its funders. They were produced by research networks, consultants and during CDBB workshops in response to CDBB briefs and are referenced here with thanks to each of the contributors. All of these are available on line at http://www.cdbb.cam.ac.uk/capability-framework-and-research-agenda. This key provides links to these reports, which are referenced by the following abbreviations throughout:

Abbreviation	***Reference***
CAR	Cambridge Architectural Research - *Defining the Research Agenda and Research Landscape for digital built Britain: Digital tools in the creation and through-life management of built assets* http://doi.org/10.17863/CAM.40460
Centres of Competence	CDBB - *Centres of Competence spreadsheet* http://www.cdbb.cam.ac.uk/files/190529_-_centres_of_competence.xlsx
D-COM	Digital COMpliance Network - *Digitisation of requirements, regulations and compliance checking processes in the built environment: Final report* http://doi.org/10.17863/CAM.40451
FOuNTAIN	Network For ONTologies And Information maNagement in digital built Britain - *Final report* http://doi.org/10.17863/CAM.40456
Gap Analysis	CDBB - *Research Landscape: Scoping Review* http://doi.org/10.17863/CAM.40461
Housing	Housing Digital Built Britain Network - *Final report* http://doi.org/10.17863/CAM.40452
Housing 1	*Housing Digital Built Britain Network - Position paper 1: How can digital tools and technologies support independent living for older people, now and into the future?* http://www.cdbb.cam.ac.uk/files/1._position_paper_ageing_and_housing_in_a_dbb_web.pdf
Housing 2	Housing Digital Built Britain Network – *Position Paper 2: What is the role of off-site housing manufacture in a digital built Britain?* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/PositionPaperOffSiteHousingManufacture.pdf
Housing 3	Housing Digital Built Britain Network - *Position Paper 3: How will the UK govern, maintain and manage housing stock in a Digital Built Britain?* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/3.PositionPaperGovernanceMaintenanceandFacilitiesManagement_web.pdf
Housing 4	Housing Digital Built Britain Network – *Position Paper 4: How could better use of data and digital technologies improve housing delivery through the UK planning system?* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/4.PositionPaperDigitisingthePlanningSystem.pdf

Phase 1 Report	Centre for Smart Infrastructure and Construction (CSIC) and IfM Education and Consulting Services University of Cambridge - *Digital Built Britain - R&D Work Stream A study for the Future Cities Catapult* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/DigitalBuiltBritain2017ResearchReportsummary.pdf
PUN	Pedagogy and Upskilling Network - *Evolve or Die: Transforming the productivity of built environment professionals and organisations of digital built Britain through a new, digitally enabled ecosystem underpinned by the mediation between competence supply and demand* http://doi.org/10.17863/CAM.40453
Sector Perspectives	CDBB – *Sector perspectives on the Capability Framework* http://www.cdbb.cam.ac.uk/capability-framework-and-research-agenda
Shojaei 2019a	Dr Reyhaneh Shojaei - *Justification for Employing the Structure and Agency Approach* http://www.cdbb.cam.ac.uk/files/justification_of_applying_structure_and_agency_feb_2019.pdf
Shojaei 2019b	Dr Reyhaneh Shojaei - *Example Insights from Applying a Structure and Agency Perspective to Key Interfaces in Digital Built Britain* http://www.cdbb.cam.ac.uk/files/example_insights_from_applying_a_structure_and_agency_perspective_feb_2019.pdf
TH	Turner Harris 2019 – *Future capabilities report: The creation and through-life management of built assets and infrastructure* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBLot7TurnerHarrisFinalPublicRelease1.pdf
UIL 1	Urban Innovation Labs – *Workpackage 1*: *Agile Standardisation Methods for DBB* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBL2CWP1AgileStandardsReport_V2.0_finalissue.pdf
UIL 2	Urban Innovation Labs – *Workpackage 2: Meta standard and Standard Landscape* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBL2CWP2MetaStandardReport_v6.0_finalissue.pdf
UIL 3	Urban Innovation Labs – *Workpackage 3: Information Pathways* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBL2CWP3InformationpathwaysReport_v3.0_finalissue.pdf
UIL 4	Urban Innovation Labs – *Workpackage 4: Comparison of COBie and IFC as information exchange structures today and in the future* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBL2CWP4ReportLRCOBieIFC_V2.0_finalissue.pdf
UIL 5	Urban Innovation Labs – *Workpackage 5: Recommendations to CDBB for the continued development of standards* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBL2CWP5Report_v3.0_finalissue.pdf
UIL 6	Urban Innovation Labs – *Workpackage 6: Design of experiment for integrating or indexing diverse or non-schema based information* http://www.cdbb.cam.ac.uk/Resources/ResoucePublications/CDBBL2CWP6ReportTestcase_V3.0_finalissue.pdf

UIL a	Urban Innovation Labs - *Making the digitally enabled services and supply chain work* http://doi.org/10.17863/CAM.40458
UIL b	Urban Innovation Labs - *Integration and optimisation of services embedded in the built environment* http://doi.org/10.17863/CAM.40459
Uncertainty	Planning Complex Infrastructure Under Uncertainty Network - *Final report* http://doi.org/10.17863/CAM.40455
Vision	Vision Network - *Final report* http://doi.org/10.17863/CAM.40454
SW – Stakeholders	Scoping Workshop (Stakeholders) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_stakeholder_value_april_2018_190626.pdf
SW – Services	Scoping Workshop (Services) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_services_april_2018_190626.pdf
SW – Built Assets	Scoping Workshop (Built Assets) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_built_assets_april_2018_190627.pdf
SW – Data	Scoping Workshop (Data) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_data_april_2018_190626.pdf
SW – Information	Scoping Workshop (Information) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_information_april_2018_190626.pdf
SW – Supply Chain	Scoping Workshop (Supply Chain) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_supply_chain_april_2018_190627.pdf
SW – Social Constructs	Scoping Workshop (Social Constructs) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_social_constructs_april_2018_190627.pdf
SW – Systems	Scoping Workshop (Complex Integrated Systems) – April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_complex_integrated_systems_april_2018_190627.pdf
SW – Context	Scoping Workshop (Context) - April 2018 http://www.cdbb.cam.ac.uk/files/scoping_workshop_context_april_2018_190627.pdf
FRW	Framework Review Workshop – September 2018 http://www.cdbb.cam.ac.uk/files/framework_review_workshop_september_2018_190627.pdf
RALW	Research Agenda and Landscape Review Workshop – February 2019 http://www.cdbb.cam.ac.uk/files/research_agenda_landscape_workshop_february_2019_190627.pdf

Key to cross-referencing

All the capabilities discussed in this framework are highly interdependent. The tags below are used throughout this document to cross-reference to other sections where appropriate and, if reading the digital version, are hyperlinks to that section. Readers may choose to follow these links or continue reading. See the Introduction for a guide on how to use this document.

These tags are also used to categorise various UK centres of competence in each area in a spreadsheet published separately (Centres of Competence).

Capability Category	Capability Sub-theme	Tag
VALUE: How to define outcomes sought, through-life value, and the best ways to pay for it	V1 Define the benefits and outcomes, how to measure them and the ways to pursue them	Defining benefits and outcomes
	V2 Turn a wide variety of wants and needs into specifications that can be procured against	Negotiating and procuring value
	V3 Find ways to make digital built Britain investable	Investability
SERVICES: How to develop and manage services that are integrated with and delivered though the built environment	S1 Define value and outcomes from asset-based services	Service outcomes
	S2 Define an architecture of 'causality' between services and assets	Service-asset interactions
	S3 Develop and manage services integrated with and delivered through the built environment	Service models
BUILT ENVIRONMENT: How to develop and improve the Built Environment across its lifecycle, embracing digitalisation	B1 Manage and protect the natural environment alongside the built environment	Environmental Sustainability
	B2 Manage the interactions between assets, infrastructure and services	Manage interdependencies
	B3 Use data, information and models to better manage assets for value through-life	Smart asset management
	B4 Develop and disseminate new digital technologies and tools	Spreading innovation
DATA: How to manage data, information and models to underpin better understanding and decisions	D1 Embed models and data as tools in understanding and decision-making	Better understanding through data
	D2 Develop and manage structures, schemas and tools	Data and information frameworks
	D3 Develop and manage (federated and hierarchical) models	Develop and manage models
	D4 Develop and manage data sets	Data and information management

GOVERNANCE: How to govern and manage digital built Britain and its most complex projects	G1 Regulate digital built Britain	Regulation
	G2 Create and manage standards	Standards
	G3 Establish a contractual regime for an integrated world	Contracting
	G4 Ensure that complex integrated projects deliver resilient integrated infrastructure	Complex projects
	G5 Embrace data and models effectively in structured decision-making	Decision processes
LEARNING AND ADAPTATION: How to adopt new tools and develop the competencies necessary to flourish	L1 Overcome barriers to adoption of new technologies, throughout the supply chain	Barriers to adoption
	L2 Define what competencies will be needed	Defining digital competencies
	L3 Utilise and exploit the opportunities to learn and adapt afforded by digital built Britain	Exploiting learning opportunities
CONTEXT: How to manage (where possible) external trends, drivers and events	C1 Detect new and changing drivers, trends and potential events	Anticipating changes
	C2 Characterise the probability and severity of future trends and events	Characterising risks
	C3 Predict likely impacts, identify pre-emptive and response options and choices	Managing responses

Introduction to the Capability Framework and Research Agenda

This document is designed to help policymakers, companies and research funders to explore and prioritise a research agenda for creating a digital built Britain. It presents a Capability Framework and Research Landscape and Agenda that aim to:

- Identify the capabilities needed to create a digital built Britain
- Signpost sources of existing expertise and research
- Support structured and informed strategy development

A companion general summary of this document is also available[1], and you may find it useful to read that before delving into the greater detail contained here. The summary gives an overview of digital built Britain as a concept and describes how each element of the framework underpins it, as well as highlighting gaps in the academic work that may form a research agenda for the UK.

The Centre for Digital Built Britain (CDBB) is working with a multi-disciplinary community across the UK to explore the implications of digitalisation, and of ubiquitous data and information across the built environment, in order to consider the capabilities needed from a range of perspectives. This report sets out a common language and framework to enable inclusive future work and discussions.

This introduction sets out to explain:

- Why we need a capability framework, how it is not exclusively a matter of developing new technologies and why multidisciplinarity is so important
- Who should read this document
- How it is structured, how to navigate it and how to find the materials on which it is based.

What is digital built Britain?

Digital built Britain seeks to incorporate digital technologies into our built assets – from homes, offices and schools to transport networks, bridges and tunnels. This digital revolution will transform how our buildings and infrastructure work and how we use them.

By harnessing data relating to the built environment we will be able to improve decision-making and achieve better performance from our buildings and infrastructure, and from the services that depend on these built assets, thereby leading to a better quality of life. This potential future, outlined in *Data for the Public Good* by the National Infrastructure Commission (2017), forms the basis of the vision for a digital built Britain.

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[1] *Developing the capabilities for a Digital Built Britain - A Summary of 'Capability Framework and Research Agenda for a digital built Britain'.* Available at: http://www.cdbb.cam.ac.uk/capability-framework-and-research-agenda.

Existing examples of digitalisation include Building Information Modelling (BIM), which, together with improved information management, has already brought about huge advances in the way the UK construction industry manages the country's buildings and infrastructure.

In 2016, the Government launched the Digital Built Britain Programme to deliver further digitalisation of the sector. Over the next decade new digital technologies such as the Internet of Things, digital twins, AI and advanced data analytics, are expected to bring about further dramatic changes, revolutionising the UK's approach to planning, building and maintaining its built assets.

Digital technologies are already transforming Britain in overt and subtle ways. Better data and information management can lead to better outcomes in terms of health, efficiency, productivity and sustainability. However, this digital revolution is vulnerable to threats from invasive surveillance, data monopolies and cyber-attacks. The Capability Framework provides a framework to pursue the knowledge and skills needed to minimize risk while moving the country toward the benefits of this digital revolution.

Why do we need a Capability Framework?

To achieve a digital built Britain, to manage it, and to enable people to live and work happily and productively within it, citizens, companies and institutions of the UK will need to develop many new capabilities.

Some capabilities can be developed by sector, organisational or individual initiatives, especially where the issue is one of co-ordination, of aligning interests and activities and of initiating the cooperation of competent people. Other capabilities will depend initially on the creation of new knowledge or the explicit creation of new systems, standards and processes. This document focuses on this latter kind of capability, and on the underpinning research that will be required. The authors of this report recognise that this is just a starting point and that the research will need to be used to create practical tools, and be resourced appropriately in order to be truly effective. Here, though, the focus is on the starting point; the know-how required to underpin the capabilities needed.

These capabilities will be wanted across the entirety of Britain. Individuals will need to develop their skills to live more effectively within a world of ubiquitous data and digitalisation. Good design can help to make this easier, but a basic level of 'data literacy' and a deeper understanding of the implications of data will be needed by everyone. Public bodies, tasked with the governance of the UK, will need to develop capabilities to use new tools and to exploit the benefits of digitalisation so they can procure and manage the services, assets and infrastructure upon which we depend. Companies will need to embrace new ways to deliver better services and assets within this evolving context. Educational bodies and professional institutions will need to teach the new skills required. All of this will take place within a world of changing drivers, trends and events which will impact the capabilities required.

The Capability Framework is designed to address all of these issues and to provide a comprehensive and consistent approach to identify the capabilities needed.

Scope

Firstly, this document has focussed on the implications of digitalisation, on the implications of ubiquitous data and information and on the ever more powerful ways of using such data and information by those involved. Secondly, it considers the increasing integration that is anticipated within digital built Britain; integration between services and assets, between service providers and asset owners and managers, between organisations across and along supply chains, as well as in the interactions between users, clients and providers. Finally, the focus is on the built environment and on the services that are delivered through, or that depend upon, the built environment. These three aspects serve to constrain the framework's scope.

This document focusses on those capabilities which have been identified as lacking in some way today, rather than on capabilities already adequate to meet future needs. It does not explore the implications of the resources required to bring the capabilities to fruition. In some cases, the starting point will be some research, perhaps followed by demonstrators, socialisation and wider adoption by practitioners. In other instances, the primary need is for leadership within the sector to align efforts and roll out changes across organisations, supply chains and professional bodies. Where opportunities for this sort of initiative have been identified, as distinct from a need for research, they have been highlighted as something the Centre for Digital Built Britain could contribute to the change agenda.

Responding to an evolving context

Digital built Britain is not an end state with precise goals for levels of digitalisation or efficiency improvements. It is a vision that will be revised continuously in response to changing capabilities and values. Decision processes, for example, should be evaluated regularly in cycles that are appropriate to the context. The contexts and drivers discussed throughout are complex and dynamic. However, we will be able to manage the built environment more effectively by continually factoring such drivers into our decision-making. Therefore, none of the capability creation should be read as a one-off exercise or one that is divorced from the wider context. This Capability Framework should be viewed as a living document that is updated as needs change and as we progressively build our capabilities and reach out for more.

The capabilities are not set out in a uniform level of detail across this document. In some areas the way forward is less evident; in others there has been considerable input and insight. For some topics, other sectors can provide ways forward, while some aspects that are unique to the construction sector will require unique solutions. Considering the scope of the document as a whole, the intersections of these topics are live, and will be further developed in the years to come. This Research Landscape and the next steps required are considered in brief at the end of this document.

It's not all about new technologies

The creation of digital built Britain is not, primarily, a technology issue. In most cases the technologies are already available or else can be developed, the tools can be built, and the solutions can be found. The most challenging capability is that of being able to decide what should be done and the priorities that should be applied. We also need to be sure of realising benefits in excess of costs so that the journey to digital built Britain is investible. Currently these three tasks of articulating and agreeing outcomes, of setting priorities and of assuring a commercial return are the most difficult.

Where technologies are involved, this document does not advocate specific solutions, although they are occasionally used as illustrations. Any solution is likely to be, at best, temporary and the key to success will be the ability to continually rebuild and adapt the tools and solutions to take advantage of data, information and digitalisation.

The need for multidisciplinary frameworks

We need to find ways for all the knowledge and good practice that exists to be shared and applied more widely. The digitalisation of the built environment is characterised by considerable activity, with many people developing expertise and tools, but most of it without any co-ordinating framework. This makes it difficult to learn lessons, to disseminate insights, or even to find sources of expertise and experience. Despite much useful work being undertaken, the research landscape lacks coherence and clarity of purpose. Many projects are being conducted that involve the application of new approaches to very specific problems, in particular sectors, with no mechanism or intention of comparing and sharing with other sectors. Hence, while these sorts of projects help build the capability of their immediate participants, others are not able to benefit.

This is not a new finding. The work of the Foresight Future of Cities Project's Lead Expert Group (Foresight, 2016) commented in mid- 2016 that, 'there is a considerable knowledge base, though it is often spread across disciplinary perspectives and not fully integrated.' Only by building frameworks within which people and organisations can position their contributions, and from which others can learn, will we ever achieve more than a series of anecdotes among researchers and their collaborators. The pursuit of digital built Britain needs an overarching, capabilities-based approach to research, with an emphasis on designing research, projects, prototypes and demonstrators with the specific objective of building competence and capability beyond the immediate participants.

Who should read this document?

This document frequently uses the words 'we' and 'our' when referring to the development of capabilities. This is shorthand for a complex and potentially contentious collection of stakeholders in digital built Britain, and it includes academic researchers and institutions; research funders; policymakers at all levels of government including regional and local; business leaders and professionals in the Architecture, Engineering, Construction and Operation (AECO) sectors; and private sector organsiations (large and small) that provide services or the built assets that house them. 'We' refers to those living, working and operating in the UK who have some role in driving the direction of digital built Britain. This vast coalition reflects the diversity of potential audiences for this document.

The Capability Framework and the Research Landscape and Agenda presented in this document provide tools to help strategists to marshal the development of capabilities needed to create a digital built Britain. Many bodies will want to contribute to the definition and development of digital built Britain, including Government departments, research councils, charitable funders and commercial organisations. Each will have their own specific interests, ambitions, objectives and targets. This document aims to help each of these audiences to define the important capabilities needed by the UK, to prioritise these in light of their objectives and timeframes, and to identify and procure the necessary research.

How to use this document

The Capability Framework has an extremely broad scope and will attract a diverse audience. Therefore, this document has been designed to be read out of order as well as in its entirety. The table of contents, Key to cross-referencing and Index all serve as ways in to the detail of the document for those not wishing to read it as a narrative. A great deal of overlap and many interconnections exist between the capability categories. These interconnections are highlighted throughout with hyperlinks to other parts of the document, enabling the reader to jump around through the wider scope of the document, again without having to read it cover-to-cover. The structure of the document, navigation aids and supporting materials are discussed below.

Finally, the Research Landscape and Agenda describes an overview of the state of research relevant to each element of the Capability Framework. This research is characterised by its availability and suggestions are made for the way forward. This section also links to a list of some of the UK centres of expertise that are already working in relevant areas. Funders and researchers can use this to make connections and put together interdisciplinary networks.

The structure of the document

The Capability Framework comprises seven capability categories formed around clusters of complex challenges relating to the creation of digital built Britain. Each category is described in its own section, which begins with a brief overview and then delving into the detail to discuss all the capabilities involved and the research topics that might be relevant to support these capabilities:

- Stakeholder value: How do we define the benefits and through-life value of a digital built Britain and how do we pay for them?
- Services: How do we develop and manage services embedded in the built environment?
- Built environment: How can we use digital technologies to develop and improve our buildings and infrastructure?
- Data, information and models: How do we manage the data involved and use it to create integrated models of our infrastructure and services, and then use those data and models to make better decisions?
- Governance: How do we determine the best way to regulate a digital built Britain, to manage its complexity and to make decisions that people will support?
- Learning and adaptation: How do we identify and teach the skills that will be needed to live and operate in an increasingly digitised environment?
- Context and drivers: How do we respond to the constantly evolving drivers, trends and events that will impact the development of a digital built Britain?

Each of these categories is described independently in this document, but they are tightly interlinked, as explained in the summary to this document.

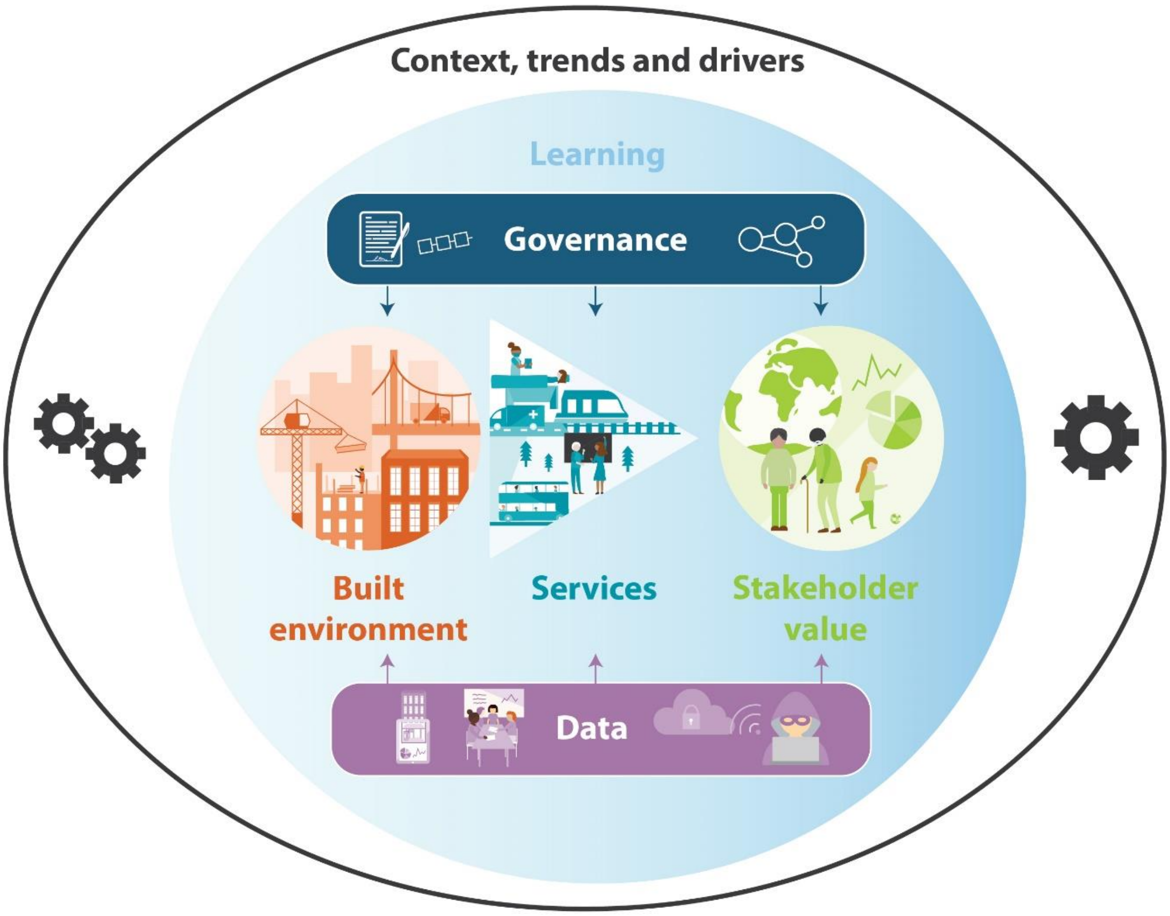

Figure 1 - The Capability Framework is comprised of interacting categories of capability within an overarching context.

The Capability Framework is followed by:

- **Research Landscape and Agenda**: This section describes the candidate research topics to support each of the capabilities and assessed the readiness of current research for uptake. It recommends next steps in light of this agenda. It links out to a list of some of the centres of competence in the UK that are addressing some of the capabilities listed above.
- **Glossary**: The specific usages of several terms found within this document are defined in a glossary. This may be a useful first port of call for the reader, as it is not referenced from the body of the text.
- **Index**: The index to this document aims to help researchers and others to enter directly into the detail of the Capability Framework.

Navigating this document

This document features a consistent colour scheme to refer to each of the capability categories (shown below), as well as an alphanumeric system for referring to the capabilities and sub-capabilities. The letter refers to the capability category and the number refers to the sub-capability. For example, 'B' = Built Environment, referring to the capability to develop and improve the built environment, meaning that 'B2' refers to the second sub-capability, that of managing the interactions between assets, infrastructure and services.

VALUE | SERVICES | BUILT ENVIRONMENT | DATA | GOVERNANCE | LEARNING AND ADAPTATION | CONTEXT

The sub-capabilities are vast areas for exploration in their own right and, in several instances, some of the detail at this level is teased out. Headings within those sections signpost underlying capabilities that support the capabilities listed above them.

As discussed elsewhere, the categories in the Capability Framework are tightly interlinked and interdependent. Where these connections are most pertinent to the discussion, they are highlighted using cross-links. If you are reading a digital version of this document, these references are hyperlinked to the relevant sections. To get back to the page you were reading when you followed a link in the PDF version, use one of the following sets of instructions:

Windows users: Alt + Left arrow key

Mac users: Command + Left arrow key

If you are reading a printed version, the cross-links are clearly labelled with the tag for that section. For example, a link to the section discussing the capability to use data, information and models to better manage assets for value through-life will be labelled with a tag, for example: Smart asset management – B3. A complete list of these tags and the sections to which they link is provided at the front of this document (Key to cross-referencing). These tags are also used to link these topics to a selection of UK-based research centres and relevant bodies that are leading on them. You can find this list as a separate document, the Centres of Competence spreadsheet.

Sources and background material

This document draws heavily upon workshops, reports and commissioned studies co-ordinated by the Centre for Digital Built Britain. These resources are gathered together and can be found using the Key to supporting materials. These are valuable documents in their own right, involving considerable effort on the part of academic and private sector participants from across the UK. Please refer to these documents for more detail about the supporting evidence and reasoning underpinning the Capability Framework. The documents also provide further insights that will be valuable in the pursuit of digital built Britain.

Digital built Britain and its creation is evidently a topic that is much wider than the technologies associated with digitalisation of the built environment. That being the case, in developing the Capability Framework, the authors explicitly looked at the implications of taking different perspectives on the wide range of topics involved. This was accomplished by exploring the systemic issues, by establishing a variety of academic networks, including a network that took a specific perspective (Housing), and by actively pushing the boundaries of the topics explored well beyond the merely technical.

The authors of this document also considered the implications of applying a social science perspective to the Framework. First, there was a review of specific instances of applying structure and agency models to a relevant application (Shojaei, 2015). Then the benefits of applying such an approach were justified (Shojaei 2019a). Finally, the approach was applied to key parts of the framework, specifically the key social interactions to be found at the interfaces between stakeholders, public institutions and private suppliers. This highlighted topics that deserve more detailed investigation (Shojaei 2019b).

By reviewing the frameworks from this perspective, it is evident that an important capability for the UK to develop digital built Britain will be the application of the tools of social science to the forecasting and interpretation of digital built Britain. This will enable us to derive insights that will underpin better decisions and enable more effective implementation with a deeper understanding of the social dynamics at play, as well as the demonstration and adoption of new technologies.

This document is not a literature review, but rather a signposting and positioning document. The academic and grey literature cited, therefore, should not be considered as exhaustive but rather as an indicative starting point for the interested reader. By the same token, mention of sources should not be regarded as commending or privileging them. This report aims to fill a gap because few authors have attempted to discuss the future of digital built Britain at such a wide scope, but deeper literature reviews that retain this interconnected view would be a valuable initial contribution.

STAKEHOLDER VALUE: Discern, articulate, negotiate and define value within and derived from the elements of digital built Britain

The introduction below provides an overview of the **Stakeholder value** category of the Capability Framework for creating a digital built Britain.

Click here for an introduction to the **Capability Framework** as a whole, including links to all the categories involved.

Stakeholder value capabilities

How to define value derived from digital built Britain and find the best ways to pay for it

- Envisage, explain and characterise digital built Britain, its benefits for and impact on the people, the economy and the environment (V1)
- Assimilate wants and needs from diffuse and varied user groups and translate into procured services and assets for the public good (V2)
- Internalise corporate value and find approaches and business models to make digital built Britain investable (V3)

Introduction

The development of a digital built Britain is not, first and foremost, a matter of developing new technologies. The primary issue is deciding what we want and how to pay for it. Much of the technical capability is available, but because any return may be received long after the investment has been made, and because capturing and monetising the value presents many challenges, the business case for investing in the necessary capabilities is often difficult to make.

The need for work in this area is shown by the continuing calls for a 'vision' for digital built Britain, for a 'value proposition' or in the questions about 'who is the customer' for digital built Britain. All these are evidence of the difficulty in satisfying the many different stakeholders involved.

In an increasingly connected world, in which data permeates the built environment, how can we ensure digitalisation contributes to productivity and happiness rather than to the dystopian? Furthermore, in the face of today's growing challenges, from climate change and austerity to social media as the primary vehicle for political debate, it becomes increasingly difficult for public bodies to make decision about the best way forward. What services should they procure, what infrastructure is needed and how can they determine the trade-offs required when stakeholders needs vary and resources are severely constrained?

Tackling these challenging questions in order to make the best decisions requires an intricate set of processes and capabilities. Firstly, we need to find ways to discuss and compare the tangible and the intangible. We have the ability to put numbers to productivity and to investment; but we also need to be able to consider such things as social cohesion.

We must devise better ways of depicting the future so that people from different backgrounds (and those in different organisations and government departments) can see what their shared future might look like. We must also find ways to balance the need to build housing and infrastructure with the necessity to protect and enhance the natural environment. If we improve our ability to make choices, then maybe we can improve our ability to specify the outcomes and outputs we want.

Frameworks and models could underpin new capabilities in understanding cause and effect and feedback loops and help us to determine the best choices to make in complex situations where the impacts are difficult to predict. A range of frameworks and models are likely to be needed to fully explore the effect of the digital on the lives of citizens and their built environment.

People's behaviour can provide an indication of the things they value – so can social scientists help us identify what people might value in a digital built Britain? Frameworks and models could help architects, engineers, social scientists and policymakers have a meaningful, auditable debate about the best outcomes and how to achieve them. Making people's mental models explicit enables them to be discussed, shared and used by decision-makers.

Computer models can also be used to predict the future behaviour of assets, services and businesses, and of the complex systems of which they form a part. The models will support discussion and debate and enable cost-effective and low-risk experiments, and hence build deeper understanding and insights.

The capabilities highlighted here are, in large part, focussed on creating better frameworks for thinking, and better models for supporting insight and decision-making. We need to develop the ability to articulate the outcomes that we seek, and to explain why we believe a particular policy intervention will get us there.

And, finally, we need better ways to measure and understand costs and value, especially over time. The much-vaunted benefits of a digital world often accrue in different places, or at a later time, than the investment that created them. A vitally important capability, therefore, is to understand the interplay of investments and returns to help us create commercial mechanisms that make digital built Britain investable – for organisations of all sizes. If paying more for a 'digital' building will save the occupants money in the long term, how much more is it worth paying now – by whom and to whom? If pervasive nets of sensors, linked to digital building controls, will save energy and carbon emissions, then who pays the installation bills today to help users in the future? What is 'best value' and who makes the decisions when council budgets are on the line and corporate performance is reported quarterly?

V1 Envisage, explain and characterise digital built Britain, its benefits for and impact on the people, the economy and the environment

Throughout the journey to digital built Britain it will be essential to maintain a clear view of the outcomes to which the UK aspires and to develop a clear picture of the best ways to manage the built environment and services to achieve those outcomes. Doing both these things requires two significant capabilities within the UK, distributed across large constituencies: the ability to formulate and articulate opinions and perspectives; and the ability to build and share an understanding of how particular activities and initiatives contribute to specifically targeted outcomes and hence the trade-offs inherent in a multi-stakeholder world. In other words, the key capabilities are how to explore and debate what is wanted, and how to discern what levers to pull.

With these two abilities there will then exist the foundations for setting direction and then investing to move in the chosen direction. Note specifically, the intent here is not to decide the direction, but instead to assure the capability to do so. The development of a third capability, that of defining the indicators of performance and success will confirm the degree of clarity achieved about intent and approach. If it proves impossible to monitor direction, that suggests flaws in the previous two capabilities. So, the constituent capabilities here are:

- To explore and debate the outcomes, purpose and role of digital built Britain in the society of the UK and its evolution (V1.1)
- To define coherent and consensus views on the linkages between activities, outputs and outcomes within digital built Britain (V1.2)
- To define and use measures of performance (KPIs) that enable the management of outcomes (V1.3)

V1.1 Explore and debate the outcomes, purpose and role of digital built Britain in the society of the UK and its evolution

Defining and debating outcomes for society is contentious; with myriad considerations and multiple opinions, from stakeholders with different priorities, constituencies and power dynamics. And all this in the certain knowledge that the continued digitalisation of the built environment will change nearly every aspect of society.

However, the capabilities needed are easily defined, but not easily acquired. They are:

i) to build a framework that allows description and discussion,
ii) to understand and articulate the outcomes that might matter, and,
iii) to articulate and communicate the candidate choices. (The making of decisions is covered in the next section.)

i) Build a framework that allows description and discussion

A starting point is the ability to choose or build a framework within which to conduct the exploration of outcomes, roles and purpose. There are many candidates already, including the United Nations' sustainable development goals, which has the advantage of comprehensiveness and scale, together with a large pool of prior experience and reference cases (UIL b, p. 54). Other frameworks continue to be developed, especially in the context of smart cities[2] and smart city pilot projects (Appio et al., 2017). It will be a difficult task to build and agree appropriate frameworks which can provide a logic, a vocabulary, and a structure to hold the concepts and organise the continuing discussion. Indeed, the UIL literature review identifies work that has compared many of these frameworks (UIL b, p. 34) and suggests that starting anew is not sensible. Instead they argue that it is better to explore existing work and make use of current structures and analyses (UIL b, section 3.2).

There is an important decision to be made here to underpin this capability; choose and use a current framework, acknowledging its potential limitations in the context of digital built Britain, or build yet another new framework? In either case, such a framework would need to transcend government department silos, sector boundaries and other organisational constructs, instead reflecting the concerns of the people and organisations of the UK. This will be essential to address the difficulties seen today in creating propositions, allocating values and costs and developing action plans across organisational boundaries (UIL b, pp. 63, 65). The result must balance completeness with accessibility and enable the many different forms of value to be discussed; must grapple with philosophical issues such as the impact of digitalisation on the future of the UK; and must enable pragmatic discussion and agreement on outcomes. In this way it can act as a basis for the procurement activities (V2) of policymakers and decision-makers and for an exploration of the value propositions and business models (V3) that will make digital built Britain investable.

Such a framework would enable a coherent comparison of the myriad smart city and smart infrastructure pilots and demonstrators, past, present and future. Data, Information and Models (DATA) discusses the increasing significance of computer models and their underlying data and information as tools for understanding the world and for taking decisions and actions. This framework must encompass the ability to include such models and include the myriad sources of data and information (Enzer et al., 2019). Making the framework inclusive will prove a challenge, but omission of any aspect from the framework runs the risk of that aspect being disregarded in all that follows.

ii) Understand and articulate the outcomes that might matter

The second sub-capability here is that of identifying the outcomes and the sources of value from digital built Britain. Are we able to find the full set of outcomes and describe them in meaningful terms? Are we able to strike the balance between banal generalities and drowning in detail? The

[2] For example, PAS 181, 'Smart city framework – Guide to establishing strategies for smart cities and communities' which emphasised the need to manage data and systems across organisational silos. PAS 181 has now been replaced by BS ISO 37106:2018 'Sustainable cities and communities. Guidance on establishing smart city operating models for sustainable communities'.

exploratory work of creating this document has unearthed many conflicting views on sources of value and outcomes to be sought. The challenge in building this capability for the purposes of digital built Britain is to control scope and depth of exploration in order to find and work with a pragmatically complete portfolio.

The definition of outcomes is complicated by the entire ecosystem within which such discussions take place. Asking the 'right question' is critical, covering aspects such as vision, objectives, stakeholders, incentives, alignment and ambiguity (Visnjic et al., 2016).

Without trying to be exhaustive, several illustrations of the nature of the capability needed and on some of the perspectives about its realisation give indications of current and potential future research. A recurring need, identified within CDBB workshops and the contributing reports is the need to work with the 'soft', the intangible and the qualitative, alongside those aspects that are seen as tangible, quantifiable, or 'hard' and therefore have traditionally been easier to track and report. While extensive bodies of work exist on these respective types of outcomes, more work will be needed to bring hard and soft outcomes into equal prominence. Negotiating the subjectivity of 'soft' outcomes will be one of the greatest challenges (RALW). This subjectivity will arise from different perspectives, different historical trajectories and the difficulties of negotiating intangibles. While there are approaches to making judgements and decisions to combine considerations of the qualitative and the quantitative, it is important to explicitly recognise and discuss the subjectivity involved. Social return on investment (SROI) and public value; quality and aesthetics; and security and risk avoidance, are just some of the potential facets to intangible value.

An exploration of value, considering design, the interaction of stakeholders, and a general exploration of how the built environment contributes to value can be found in Saxon (2014). They consider the whole value proposition and its translation into procurement. For further examples, see Environmental sustainability (B1) for a discussion about balancing the value of the built environment with the natural environment.

Social return on investment (SROI) is a live topic[3] to which the creation and maintenance of the built environment is potentially a key contributor (e.g. Egbu, 2016; Watson et al., 2016). Guidance exists today for policy-makers and public sector decision-makers on the application of the Social Value Act (Department for Digital, Culture, Media and Sport, 2012), and provides a starting point to consider the unrealised opportunities of digitalisation. Contributions from the research base could continue to inform understanding and decision-making in this topic.

Public value is another vigorously debated topic, likely to remain so for some time, and for which the discussion fora at the boundaries between academia and policymakers might be useful, examples being the debates hosted by Mariana Mazzucato[4] and the work of the Cambridge University Bennett Institute[5]. The Public Value Framework plus supporting guidance has been recently published (HM Treasury, 2019).

[3] http://www.socialvalueuk.org/
[4] http://www.thersa.org/events/2017/02/tackling-global-challenges-through-mission-oriented-innovation and http://www.thersa.org/events/2017/02/tackling-global-challenges-through-mission-oriented-innovation
[5] http://www.bennettinstitute.cam.ac.uk

Considerable work has been done on ways in which the built environment affects intangible values, for example in health and wellbeing (Glasgow Centre for Population Health, 2013), the health of the elderly (Garin et al., 2014), mental health (Moore et al., 2018), psychological wellbeing (Watson, 2018) and reduction in crime (Armitage, 2018). There are many other such studies that could make a valuable contribution to the debate, by highlighting the insights to be shared and the trade-offs to be made, and reviews on the impact of the built environment on quality of life conclude there is much still to be done (Mohit, 2013).

Digitalisation and computer-based tools have a major role to play in exploring appearance, aesthetics, quality and the fit with context. Much is being done today to underpin informed debate (Smith & Laing, 2018). The Vision Network identified that immersive technologies such as virtual reality can be used to engage with stakeholders, especially the public, to show how a built asset will look and so to enable deeper debate and understanding of potential futures (Vision, p. 25). Note also the balancing view that use of such novel technologies can obfuscate areas for debate (Foth, Caldwell, Fredericks, & Volz, 2018). Whichever is the case, using virtual and augmented reality will depend upon the data (DATA). The Design Quality Indicator[6] is one way into this and claims to affect many intangible aspects. Even definitions of the quality of a built environment have been a topic of study for more than a decade (Dempsey, 2008). In terms of designing a built environment that is pleasing, functional and of high quality, digitalisation is potentially a useful tool, but only if decision-makers use it to ask the right questions (see ***Box 1***).

Box 1

The last decade has seen the rise in council-developed housing in London that places an emphasis on design aesthetics and quality of life. The cost of these popular residences are offset by building private housing to sell off at the same time.

However, the developments are not universally appreciated. In the Somers Town neighbourhood, a tower block of 100% private flats is scheduled to replace a local park, while the social housing it will support is based around a new school that may not be needed by the residents. According to a member of the local neighbourhood forum, '"If this is the answer, then they've asked the wrong question."'

There is a delicate balance between aesthetic value, public services like education and green spaces at the micro-geographic area. Furthermore, there may be unintended impacts on quality of life by losing the park, such as fewer places for children to play, or safe spaces to cycle away from main roads. Development is a complex process, but asking the right questions is essential to untangling it.

(Wainwright, 2019)

Functional and emergent intangibles that need to be understood and sought as part of the portfolio of benefits will include robustness, resilience and security. Security is an intangible issue with very real implications and consequences (D1.4). There is considerable activity today, both research and the creation of guidance that can be incorporated in both the debate about outcomes and the pragmatic management tasks arising. Security becomes a particular issue when cyber-attack threatens infrastructure assets. Turner Harris (TH) address this

[6] http://www.dqi.org.uk/

specifically, noting the extended and complex network of suppliers, and hence the importance of security-mindedness, as a core element of people's mindsets. As well as the potential for catastrophic attacks, they point out the destructive impact of theft of intellectual property, of commercial secrets and sensitive data, especially in light of the magnitude of budgets of big infrastructure projects. The Centre for the Protection of National Infrastructure[7], the government authority for protective security advice to the UK national infrastructure, is the obvious starting point and focus for such debate.

The challenge with resilience and risk mitigation lies in valuing the 'non-occurrence of an undesirable event or outcome' (FRW). Considerable work has been done around resilience, for example the Government Office introductory and explanatory guide (Matyas, Pelling, & Foresight, 2012), which emphasised the need to make decisions with resilience in mind. More recently a literature review on the Resilience of Digitally Connected Infrastructure Systems was commissioned by the National Infrastructure Commission (UCL & Arup, 2017) and has been followed up by consultations in a further study (National Infrastructure Commission, 2019). Internationally, collaborative projects are exploring how to communicate resilience as a concept and its implications (Rome, 2018). The built environment and the management of data by the disciplines around it have much to contribute in exploring resilience to disasters (Harvey et al., 2018), but there are many strands to be aligned (Hassler & Kohler, 2014) and numerous calls for an integrative framework (Haigh & Amaratunga, 2010). Computer modelling tools are at the core of much of the insight to be gained (see also the discussion in G3 of integrated and complex systems).

How, then, are we to bring all of these intangibles into our valuations of the built environment and services and how do we know what to value? An important enabling capability is the widespread use of computer models at all levels in order to better understand value and trade-offs (see DATA). Such models may span assets, services and business, including, for example, 'BIM for Investment', suggested by Turner Harris (TH, p. 32), building the ability to construct more sophisticated models of both capital and operational expenditure, making use of simulations and later digital twins as tools to increase the certainty of estimation of both value and cost. An integration of these tools offers both value and cost wins in so many ways; financing, insurance, timing options associated with expenditure and a better reconciliation of benefits and costs. And painted on a broader canvas than just the institutional investment case, such tools can also inform the understanding and debate about what forms of value are sought within digital built Britain. Policymakers, decision-makers and, if the tools are well-designed, a broader community of stakeholders can explore choices about buildings and services, about values and costs and about trade-offs to better understand what is wanted and what might be the dimensions of the inevitable trade-offs to be made.

Another key question to ask from the earliest stages is 'Value for whom?' Many people will be affected by digital built Britain in many different ways and it will be difficult to identify them, but this must be done to ensure coverage and inclusion (RALW). This must consider users and non-users of services and the built environment among the affected. Exclusion, especially digital exclusion, threatens to undermine the provision of services to some cohorts in society (Watling & Crawford, 2010). Digitalisation will change the resources open to people and institutions, their strategies will

[7] https://www.cpni.gov.uk/

change and the balance of power will change. Market actors will interact with public sector bodies and the channels of communication and the definitions of valuable outcomes will change. This is a potentially rich area for social science research, illustrating the nature of the changes, of the interactions between actors, and between people and organisations of the UK and its built environment (Shojaei, 2015).

The number and complexity of sources of intangible value mean that scope is inevitably an issue. What are the boundaries of reasonable inquiry? Where will value be realised? We need to be explicit about the scope and boundaries we set in these debates in order to understand who or what may be excluded. For example, in various circumstances it may be appropriate to exclude or to include the rural and coastal as well as the urban; generations of the future or archaeological assets from the past; the interplay of infrastructure with the natural environment; or tourists and visitors as well as residents, all of which have been identified as potential contributions to the debate about value and outcomes (SW – Stakeholders).

Changes in the behaviours and expectations of citizens will lead, inevitably to changes in what people see as important and what they value. CDBB's Expert Group have highlighted the need, therefore, to anticipate the impact of emerging and proliferating alternative sources of data and information – for example crowdsourced pedestrian maps and self-published news sources, and therefore people's perception of cost and value (FRW). We need to recognise that the powerful companies in and around social media and data sharing will shape both the behaviours and expectations of users. Consumer industries are learning to develop their products to respond the ever-developing expectations of the 'digital consumer' (World Economic Forum, 2016a). Such changing expectations, driven by market forces, will change what is asked of the services and built assets in digital built Britain.

In the debate about value, we may need to challenge some of our deepest assumptions about how the world is organised. For example, the concepts of 'sectors', their definition and differences may prove unhelpful in a world in which these boundaries become meaningless as data enables new business models and services that reshape sectoral activity. Furthermore, focusing only on the traditional sectors associated with the built environment may exclude considering other sectors from which opportunities may arise, threats and risks emerge or from which valuable lessons can be learned (RALW).

iii) Articulate and communicate the candidate choices

Finally, there is the need to lead the discussions, to manage the fora and to distil the outcomes into a compelling form that manages the balance between fixity of purpose and sensitivity to changes that invite re-examination. Thanks to their qualitative nature, intangibles are often more difficult to communicate than more concrete forms of value, such as ROI. In both instances, however, uncertainty increases the difficulty of clearly articulating value in order to conduct a meaningful debate about the trade-offs involved. Actors in the debate about value will need the capability to understand, debate and communicate risk and uncertainty. Taking action and pursuing initiatives at a scale likely to create a meaningful difference in the outcomes for the UK will inevitably involve uncertainty and risk. Such uncertainties and risks need to be explicitly recognised, not only so that they can be managed, but also so that they can be effectively communicated by decision-makers to the stakeholders involved, discussed further in the section on decision processes (G5). This communication will be the mark of mature debate and cogent decision-making.

This will be underpinned by more subtle capabilities, for example the ability to weigh in the balance the quantifiable, such as transport capacity and school places, alongside the more intangible aspects such as aesthetics, privacy, social cohesion, security and resilience. Achieving this nuanced debate may be supported in part by disciplines outside of AECO, such as social research, change management, media and communication studies, even linguistics. Scenarios are a commonly used tool to reflect upon the future, and there are discipline capabilities to be developed here. The debate about uncertainty becomes most visible when computer models are to be used to explore possible future outcomes and questions arise about what to model and with what fidelity. Again, these topics are explored further in the section on decision processes (G5). Having explored the various perspectives and considerations, an important task is to then build the vision and disseminate it, thus articulating a clear picture that enrols stakeholders across the whole community including private individuals, government organisations and the private sector. This may not be a task for research, but it is nonetheless an important capability.

In summary, the policymakers, decision-makers and citizens of the UK need to be able to build and work within a logical framework that will enable them to articulate, explore and debate the benefits and outcomes, the value sought, and the trade-offs to be made as digitalisation transforms the built environment and its services. The articulation and discussion and, especially the trade-offs, will be made more difficult by the need to compare the intangible and the tangible. However, there is already a large body of research that can inform these debates and that would be identified, surfaced and contribute through the proposed framework. Then, able to discern and articulate the components, and their views, the policymakers, decision-makers and citizens need to be able to identify cogent options for the benefits they would like to see from digital built Britain.

V1.2 Define coherent and consensus views on the linkages between activities, outputs and outcomes within digital built Britain

In order to make directed progress towards any articulated vision of the future, all involved – and policymakers in particular – need to be able to define and articulate their understanding of the relationship between the options for action open to them and the outcomes they seek. They must be able to describe and debate their models of cause and effect and the loops between them. This clarity enables debate about the potential pathways and their pros and cons. A substantial body of work in this area has been conducted within policy evaluation, focusing as it does, on discerning which interventions had the most impact and why. Building this capability will also require multidisciplinary work within a systems-thinking context, as advocated by Shrubsole (2018), to avoid the risks associated with asking the wrong questions.

Creating such models of dependent relationships in a decision space is difficult, more so is creating the mechanisms to debate between them and choose which to use. But without this capability it is impossible to begin to predict outcomes and thus have an auditable process for deciding policy. Example questions that arise in this regard are:

- How do policy initiatives translate into 'outcomes' for different components of the UK's society, economy and natural environment in the digital built Britain of the future?
- What are the factors and mechanisms by which outcomes and value are being created and captured via services provided, built assets created, data and information gathered and used, or the subtle interplay between each and all of these?[8]
- How should the built environment be developed and managed to deliver value, both directly and by supporting service provision?
- What happens to value creation as the boundaries between services and assets blur, as sectors overlap and as the interplay between public and private institutions, across supply chains and between commercial partners changes over time? (RALW)
- How tightly coupled are the interactions between sectors and between assets and services? Where does overspill occur into adjacent sectors, with unintended consequences? How quickly will things happen in this instance?
- What might be the role of interventions that influence the demand for services within the built environment? For example, how might reducing home energy demand through various social and technical mechanisms impact the demands on energy infrastructure? What part might demand management play and how is this to be balanced against the ethics of culturally or contextually differing values and agendas?

This thinking is important for policymakers, but it also offers an opportunity for commercial decision-makers to understand government expectations. Sharing, between decision-makers across the network of actors, evolving and negotiated views of how the world works, enables more nuanced debate and thus better understanding and better decisions throughout the complex networks that will characterise a more integrated world.

Inter-relatedness and interdependencies must be explicitly considered in such modelling, both via the interaction in complex integrated systems (Kalyviotis et al., 2018) (see also systems integration in G4) and via other less obvious cross-coupling such as interrelated legislation and regulation (addressed further in the section on regulation G1).

Understanding the systemic interactions offers ways to identify and abstract more value, while failing to identify interactions can be a source of value destruction. Carhart et al. (2018) explore this, providing illustrative instances and a structured systems approach.

The capability to define consensus on interdependencies can be built in many ways. As well as exploring the assumptions and uncertainties that are present within a situation, there is room for greater discussion and debate to achieve a shared clarity about the mental models and world views that are in use. While these are implicit it is difficult to surface hidden assumptions or conflicts. Policymakers might create mechanisms by which mental models can be articulated and negotiated, while researchers can explore the process of making implicit models explicit (DATA). Although there

[8] Described as a capability to articulate how, 'the causal relationship between the infrastructure and value of service socioeconomic outcome is defined' (UIL a, p. 80).

are early discussions of this (Moglia et al., 2018), there is still plenty to be done to develop this capability.

A powerful approach is to translate such models to systems diagrams (Williams, 2013) and, where feasible, to subsequently develop computer models that can act as tools for enhancing understanding, exploring and making decisions. The continuing development of new and more insightful models from both social scientists and engineers is a central requirement here (RALW). The 'Theory of Change' approach argues for articulation and modelling of outcome *before* exploring the interlinking factors, especially those in societal and organisational change[9]. Application in the built environment has focused on sustainability and on health outcomes, but the potential exists to address a wider range of topics.

This capability will be evidenced by clear and accessible articulation of policymakers' and decision-makers' mental models of the linkages and leverage between candidate actions and the outcomes envisaged. Always it is essential to be clear about the scope of discussion and the scope and depth of modelling to ensure that both are appropriate and well aligned. Clear and published mental models can be audited and debated by others, linked back to the framework discussed in the previous section and thus contribute to better decisions and better-targeted actions.

V1.3 Define and use measures of performance (KPIs) that enable the management of outcomes

One test of the robustness of capabilities V1.1 and V1.2 is to measure the success, either of outcome or of process. What key performance indicators would confirm success and would also meaningfully indicate gaps and directions for enhancement? Measuring value needs to be considered, not just in terms of the initial procurement, but also through life, especially for long-lived assets such as buildings and infrastructure. There is a well-established stream of work considering this, including for example, the development of toolkits for assessment (Scottish Futures Trust, 2016). Interesting work on performance indicators looking at outcomes from integrated infrastructure as a forward-looking process (Dolan et al., 2016) has been applied within sectors (Carhart & Rosenberg, 2016), but not yet across interacting sectors. This exploration of systemic contributions to outcomes will be important. Furthermore, articulating the value of outcomes from supply of services is seen as key to success, especially when there is a chain or ecosystem of partners (UIL a, p. 56).

This is an important capability for two reasons. Firstly, it augments the other two and, developed successfully, confirms their validity. Secondly, there is a skill in designing good indicators which are minimally subject to Goodhart's Law (Koehrsen, 2018), which states that as soon as a metric becomes a target, it ceases to be effective as a metric. Examples of this thinking can be found in Keirstead (2018), a product of the EPSRC-funded scoping study, 'Metrics, Models and Toolkits for Whole Life Sustainable Urban Development'[10] and in the development of tool kits for assessment

[9] Identified at (RALW, p. 24).
[10] http://www.sue-mot.org/

(Scottish Futures Trust, 2016). The National Infrastructure Commission also identifies the need for effective measures (National Infrastructure Commission, 2017b, p. 37; Annex A).

However, to close the loop back to the choice of outcomes to be prioritised, it is important to discern the ways in which evidence is to be used, especially in highly politicized debate, and how the framing of measures, the evidence and the outcomes sought is so tightly interlinked (Parkhurst, 2017).

Deriving value from digitalisation presents its own challenges because of the transformational and generative potential from ubiquitous data and new tools. Despite the amount of work on smart city projects, 'strikingly little research has been conducted on the evaluation of smart city interventions and the measurement of outcomes of embedded smart technologies for cities and citizens' (Caird & Hallett, 2018), in part due to the absence of a causal frameworks linking inputs and impact. A clearly articulated theory of change should be at the core of an evaluation of the interventions that will lie at the centre of developing digital built Britain (UIL 3, p. 32), and certainly for any demonstrators or pilot projects proposed (Robinson, 2016).

Flagship research undertaken at Bristol is indicative of the way forward here in engaging and debating these key issues and creating an integrated diagnostic framework[11]. Computer modelling may well have a role here by enabling the inference of variables that cannot be directly measured and, of course, in monitoring the progress of any particular intervention towards its intended outcomes.

So, in summary, the UK will need to develop capabilities to design a portfolio of benefits and outcomes and to set direction by choosing the best portfolio of actions, based on an ability to explain how and why this particular mix of activities would lead to the benefits sought, recognizing that many of the outcomes will be intangible, and then finally to being able to define how to measure progress along the journey.

V2 Assimilate wants and needs from diffuse and varied user groups and translate into procured services and assets for the public good

Whereas the previous section describes the capabilities necessary to explore the creation of the big picture, here the focus is on the capabilities needed by those defining, procuring and managing the services and supporting the assets that deliver public good. The people doing this are tasked with acting on behalf of the body politic and need therefore to have the clearest possible understanding of the trade-offs to be made and the outcomes sought. But perhaps the greatest challenge lies in defining and specifying the details about assets and services in ways that ensure public value.

The constituent capabilities here are:

[11] http://www.bristol.ac.uk/cabot/what-we-do/urban-id/

- To discern, articulate and negotiate prioritised through-life value and expenditure on behalf of users and non-users (V2.1)
- To negotiate, decide, articulate and communicate value priorities (V2.2)
- To translate needs and wants into meaningful specifications (V2.3)

V2.1 Discern and articulate prioritised value through-life value and expenditure on behalf of users and non-users

As digitalisation becomes more pervasive, so the community of people affected increases. In part this is because of the greater integration between services and assets It is no longer just about a building's occupants, but now it needs consideration of the beneficiaries of the services as well. Furthermore, consideration must be given to 'non-users' or to people who make use of the assets and services in unconventional ways. To what extent do skateboarders occupying a civic space represent social cohesion in a manner that discourages crime? Does camera surveillance of privately-owned spaces drive unwanted behaviours to areas where the occupants are less resilient, for example to where homeless individuals may become victims of more frequent and vicious crimes[12]? How is value experienced by all the parties involved in these transactions?

The starting point here is the ability to identify the full range of stakeholders – whether they are users of the services and assets, peripheral or non-conventional users, or even non-users – and to engage with these stakeholders. This identification of stakeholder groups of different social characteristics, of different purpose and role, and of different interests is difficult. It is important to consider the potentially and actually marginalised. Although work has been done in this area[13], the problem for the policymaker remains. There then needs to be efforts made to find ways to represent the interests of those who might otherwise not be considered, including future generations[14].

Having identified the various interest sets, there then arises the need to discern value by engaging the targeted parts of the community. So, how best to enrol and engage stakeholders and how to be complete in coverage and in representation? It is possible that digital tools may support this capability though the use of digital tools to better engage with citizens and users throughout the design process (SW – Stakeholders). What might be the lessons from early experiments (e.g. Laing, 2018)?

Engagement with community stakeholders is recognised as challenging, but it is an area of work across the world and there exist compelling examples of guidance and good practice in the UK[15] and elsewhere (State of Queensland, 2017). A review of the area by Leyden et al. (2017) discusses the

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[12] See also the concept of hostile urban architecture, which uses design to prevent people from loitering in certain spaces (Lo, 2017; 99% Invisible, 2016).
[13] http://gtr.ukri.org/project/D8FC1721-159F-42EE-90E5-3A6151D1BDC7 and http://esrc.ukri.org/news-events-and-publications/impact-case-studies/mapping-uk-s-internet-inequality/
[14] See Wales' Wellbeing of Future Generations Act for legislation that encourages the inclusion of these stakeholders in decision-making processes: http://futuregenerations.wales/about-us/future-generations-act/
[15] http://www.communityplanningtoolkit.org/

need for customised approaches and solutions, and highlights ways in which the process run well can increase enrolment and commitment, while noting the dangers of exclusion and engendering cynicism from a poor process. Tyler & von der Tann (2016) explore the issues of engagement and communication through the whole lifecycle of infrastructure, discussing links between vision and decision. See also G3.2 about communication of decisions.

While there is extant work in this area, there is still much to be done to explore how digitalisation can be used to enhance performance of public services and assets. Some digital technologies offer exciting options to enhance and enliven engagement. Some experiments are underway, using digital tools to gather insights, such as Cityswipe[16], which has been described as 'Tinder for cities', the Manchester call for sites for built development[17], and tools such as Participology and its international case studies in engagement.[18] Computer models of the built assets, together with models of services can provide core models and data, upon which can built the immersive technologies of virtual reality and augmented reality, for example 'Urbanplanar'[19]. This is one of the use cases identified by the Vision Network (Vision).

Some practitioners have already thought explicitly about the implications of digitalisation in community engagement (Fredericks & Cochrane, 2015), giving valuable examples and pointers to the future. Others use digital technology to increase the participation of stakeholders in decisions about the built environment (Leyden et al., 2017). However, participation – particularly through digital means – is not guaranteed. There are valid concerns about the dangers of the 'digital divide' (see LEARNING), and the need to invest specifically in outreach and inclusion, especially given the drive to digitalise public services. The need to avoid marginalisation or the increase of individual risk of exclusion should be a precursor to a new digital service implementation, rather than an afterthought (UIL b). Others note the difficulties of converting model outputs into formats that are accessible to non-specialists (Jin, 2018), suggesting that this will be an important aspect. There is great potential here for a taxonomy of approaches and tools, an assessment of what methods work best under what circumstances, and signposting of future prospects and issues in the light of digitalisation. This is an area with considerable research covering topics such as the proliferation of the internet, uptake of ICT technologies and the design of physical devices, human-computer interaction and user experiences. The key here is not to re-invent this research but to adopt what is relevant.

The next sub-capability is that of discerning, understanding and articulating the values, wants, needs, preferences and priorities of people, of stakeholders, and of interest groups and sets (Shojaei 2019b). As explored in V1.2, often the value sought by stakeholders will be intangible, for example 'safety', addressed for example by explorations of design and crime in the built environment (Armitage, 2017). In other cases, the value sought may be emergent and maybe even unexpressed, such as resilience against natural disaster. But policymakers need the capability to collect and consider these various (and maybe competing) demands. This may entail translating implicit mental models into explicit ones, characterising considerations of prosperity, social cohesion, sustainability

[16] http://www.dtsmcityswipe.com
[17] http://mappinggm.org.uk/call-for-sites/
[18] http://www.participology.com/case-studies.php
[19] http://cyberbuild.hw.ac.uk/projects-urbanplanar.html

and other subtle elements of value impacted by digital built Britain. It may require active interactions to bring out subtleties and unarticulated issues. Examples of this in action include the Urban-ID project exploring how features of the urban environment affect happiness[20] and the Milton Keyes Smart City project's engagement with citizens[21]. Tools can be built to support this identification of need and search for value, for example the mapping of stakeholder 'journeys', tasks and activities to identify unmet needs and opportunities (UIL 6).[22]

As in so many instances, the action required now is to take the lessons from previous work, to translate them into a coherent whole that could underpin a capability and then to embed that across the UK in support of digital built Britain. To do so will demands an understanding of which elements can be made into procedures, identifying which elements can be supported by tools and platforms, and selecting which might be the target for pilot projects and demonstrators conducted as part of a focused capability-building exercise, all while managing trust and confidentiality[23].

Finally, as discussed in V1.3, there is the challenge of articulating and communicating the agreed outcomes that are sought in order to unbundle them. This will indicate to stakeholders the mix and the priorities for attributes such as 'a sense of place' and culture; security; cohesiveness and inclusiveness; shelter and the absence of homelessness; transportation choices and variety; diversity and inclusiveness; design and operation for ecological sensitivity; and alignment with regeneration strategies (Phase 1 Report).

V2.2 Negotiate, decide and articulate value priorities

Marshalling the outcomes from deploying the capabilities discussed above, the next step is to make and communicate decisions, negotiating trade-offs in ways that are regarded as legitimate by all involved. Underlying this is the capability to make good decisions, considering participants, fora, processes, activities and tools appropriate for the digital built Britain of the future, covering the many constituent aspects, for example the ability to:

- Design good negotiation and decision-making processes in digital built Britain
- Manage context, scope, change, and timeliness of decisions
- Combine the qualitative and quantitative outcomes in valuations and make the implicit explicit
- Understand and manage the implications of uncertainty of all kinds
- Manage time and timeliness, both initially and in monitoring, reviewing and re-visiting decisions
- Manage the interface between decision-making entities and with policy / regulatory / legislative frameworks

[20] https://www.bristol.ac.uk/cabot/what-we-do/urban-id/
[21] http://www.mksmart.org/citizens/
[22] Highlighted in (SW – Stakeholders, p. 12)
[23] Key issues flagged up in (SW – Stakeholders)

- Use decision-support tools to make better decisions

The Uncertainty Network suggest several dimensions to enhance decision-making capabilities, including clarifying the value of *a priori* analysis, disciplined use of scenarios and a true dialogue between analysis and decision-makers (see also Uncertainty, G5). Other components to be developed for this capability include question-posing, boundary-setting, sense-making, data quality, model quality, option formulation and all other elements of complex (distributed and interacting) decision-making over time and through-life.

Intangibles and incommensurable comparisons are identified frequently as big challenges in making decisions about digital built Britain. Evidence exists, for example, about demands for aesthetic considerations in housing (Prince's Foundation, 2014), but how best to prioritise? What are people willing to pay for intangibles? What might be the trade-offs to be made between health, transport, housing, education and so on? Developing the capability to manage such trade-offs will require redefinition of boundaries, between sectors, between typical government and organisational boundaries and between responsibilities of decision-makers. Some of this might be underpinned by new processes. Ethics will play a large part in these decisions. But who gets to choose? Whose priorities will dominate? Given the inter-relationships involved who loses when others win? Urban Innovation Labs (UIL b, section 4) suggest that these matters of ethical choice be linked explicitly to the frameworks used to identify value (V1).

Technological tools and methods will be needed to underpin this capability. However, such tools and the decision processes they support must be designed and used with a deep understanding of the outcomes that will be subject to changing context (C3) and different degrees of uncertainty (G5) in all the inputs. In all of this, the Aqua Book remains a core source of guidance about the analysis necessary to underpin good decision-making (HM Treasury, 2015b).

This ability to make difficult decisions must be used through the life of services and assets and in order to monitor outcomes, subject to changing contexts and maybe in the face of major changes in priorities. Policymakers, decision-makers and managers will need to new and creative measures to compare sources of value including intangible externalities (Uncertainty, p. 2; UIL a, p. 79). Utilising and extending existing research on how design decisions underpin the success of public spaces, for example, can help ensure that the built environment contributes to a sense of community, physical wellbeing, and other outcomes that evince stakeholder value (Carmona, 2019). All of this links to the capabilities discussed in the SERVICES, BUILT ENVIRONMENT and DATA sections on the through-life management of each.

It is also important to define, manage and signal legitimacy and responsibility in all the above (see ***Box 2***),

Box 2

Digitalisation can impact the signalling of legitimacy. For example, because a prisoner may remain in police custody during a video-linked trial they may lose sight of the fundamental difference between the police and the judiciary, so undermining one of the tenets of our justice system.

Such aspects exemplify the ways in which digitalisation associated with decision-making is a subtle and on-going topic for debate (Ward, 2015). This raises interesting questions about jurisdiction when one 'service' is happening in a building belonging to another.

for example, how to define and allocate legitimacy and responsibility in a digital and integrated world where there may be new and less-obvious actors, how legitimacy and responsibility is established and signalled, and how the changing boundaries of legitimacy, responsibility and authority will change and as integration and as digitalisation enable new structures and dynamics.

The final step is the communication of decisions about priorities – and especially any decisions to change priorities. Achieved well, such communication maintains trust and accountability, and vice versa (ICAEW, 2011, section 5).

Integration of services and assets, of adjacent systems and of more complex supply ecosystems will broaden the range of those affected by decisions and hence communication will need to be explicitly planned. Communication of decisions will be profoundly influenced by digitalisation. Firstly, there will appear new tools, both to inform stakeholders and to provide discussion platforms. The audiences may be more diverse and the messages disseminated in less controlled and less predictable ways.

We will need to consider the implications of communication in a 'post-truth' world to multiple and interacting stakeholder groups. Agnotology[24] is emerging in so many domains that one might expect it to take its place in debate and discussion here also,[25] and while there is a scattered literature (Albuquerque & Almeida, 2019; Bullesbach, Cillero, & Stolz, 2017), there is not yet a coherent body targeted at this topic in the context of a digital built Britain. Such research, even if not pursued specifically for digital build Britain must be accessed and assimilated by policymakers, decision-makers and, indeed, citizens.

Current processes that perform similar functions, such as the planning process (G1), deserve attention and update, while others will need creating from scratch. One proposal (SW – Stakeholders) is for the creation of a demonstrator that develops and pilots a digital 'discussion-support platform', yet to be defined, which might underpin data and information sharing, support discussable predictions of outcomes, and enable more inclusive debate about alternatives and trade-offs. Any proposal to create such a demonstrator would need to recognise the development risk and define how lessons would be extracted, irrespective of the outcome. Decision rights associated with such modelling would be an important topic for exploration in any pilot study.

V2.3 Translate needs and wants into meaningful specifications

The final step in this chain of capabilities is the creation of specifications that make best use of digital tools and support the objectives of built assets that are designed with services in mind (UIL a), for the tighter integration of services and assets, and a better focus on accessing all the sources of value discussed above. This activity will also need to recognise the significance of the linkages discussed above and the capabilities needed to access the benefits from tighter service-asset interactions (S2)

[24] Agnotology is the study of culturally induced ignorance or doubt, particularly the publication of inaccurate or misleading scientific data.
[25] As can be seen in the debate playing out in Love & Ahiaga-Dagbui (2018) and Flyvbjerg et al. (2018).

and to manage such interactions through-life. Part of this will include creating imperatives for improving the transfer, sharing and maintenance of data and information between organisations and over time.

Ultimately, such specifications will turn into procurement. Data is already an issue here, as private organisations may need to share data and information in unprecedented ways in order to specify and commission assets in digital built Britain. Public sector organisations may also find themselves subject to legislative pressures which may drive their activities and their interaction with the built environment. For example, the NHS is required to respond to the Climate Change Act (National Health Service, 2008) and this can and will drive their procurement policies with respect to both services and built assets. But they note that their early case studies are chosen for the availability of good data (National Health Service, 2018) and that this will continue to be essential for them to make progress.

Work has been done in exploring the specification decision and the surrounding inter-organisational systemic dynamics and, although focused on the introduction of novel materials into construction applications, may create a useful starting point for further research to underpin the development of this capability (Jones, 2019).

Outcomes-based contracts are a topic of attention, especially with the potential for servitisation of assets. The Government has a role to play here, but recognises inherent risks and the need for experiments with contracts and regulation (Government Office for Science, 2018, recommendation 9). Research into approaches to servitisation and outcome-based contracts in the built environment would be valuable and could build upon the tests and pilots suggested. (See also GOVERNANCE for further discussion of contracts, G3, and regulation, G1.)

Procurement processes will, of course, depend entirely on the situation, but there is a strong link to the next capability. The processes, the decision-making and the criteria used will need to reflect the trade-offs which should be explicit in the specifications. For example, in procuring a building what trade-off is being made by the procurement authority between capital cost and energy / emissions performance? This trade-off has an impact on the business models to be used and on the decision criteria.

Finally, as the value of computer models and their supporting DATA is recognised, so the sector will need to become more sophisticated in procuring and then managing their virtual assets through life to realise the value embodied in such assets; both the models and their accompanying data and information.

In summary, this section dealt with capabilities to support procuring built assets and services that contribute to public good, which requires a robust and explicit understanding of needs and transparent processes for negotiation and prioritisation. These needs then need to be translated into detailed and meaningful specifications for procurement and planning. Digital technology can help with this process by providing better data, information and models, but they are ultimately tasks for human decision-makers.

V3 Internalise corporate value and find approaches and business models to make digital built Britain investable

In many ways the capabilities needed by the private sector – to identify where and how value can be enabled by the better use of data and information in the creation and operation of services, of assets and of the integration between them – mirror those needed in the public sector. However, the private sector has an additional imperative: the need to find ways in which to capture some proportion of the value created and to use this to enable a case for investment – realising that the costs may span the supply chain and may not align with the value created and captured.

Again, the issue is not primarily technological, but rather one of identifying and removing barriers to adoption. After all, it is seen that 'the [BIM] mandate has given the industry the push towards BIM that it needed', though there is more yet to be done (NBS, 2018). But proving the business case is vital for further and wider engagement in projects entailing digitalisation, data, information and models (Dixon et al., 2017).

Barriers include concerns around business models and information transfer across contractual interfaces, attitudes to financial risk, integration of new tools into current processes and concerns about security (TH, p. 16). Misaligned incentives, a lack of hard evidence of value, insufficient metrics and a lack of guidance for assessing benefits are also barriers (PricewaterhouseCoopers LLP, 2018). Feedback from many consulted during this work indicates that the adoption of digital tools among companies working in the sector is often impeded by commercial concerns, specifically about the risk-reward trade-offs, and a lack of visibility of the likely nature and timing of returns from investment. Individual organisations may be asking themselves why they should pay now for returns they may never realise. These barriers are likely to constrain the uptake of tools and are likely to be most prevalent among the smaller companies along the various supply chains, for whom investments can constitute a proportionately greater business risk (Housing 2). Therefore, in outlining important capabilities to make judicious investment possible in tools and technology, the focus is on the capabilities for business to discern potential value and to be able to map out a path to accessing such value, while issues of investment and fair distribution of risk remain priorities for the change agenda.

Prior work has included both the identification of benefits and the creation of a methodology for consistently and accurately estimating the benefits of adopting so-called BIM Level 2 (PricewaterhouseCoopers LLP, 2018). Work has been done on a taxonomy of BIM adoption, for example by Ahmed and Kassem (2018), and might be extensible to other aspects of digitalisation. All this provides a foundation for further demonstration of benefits as digitalisation moves beyond BIM Level 2.

Industrial initiatives such as Project 13[26] have explored adopting an 'enterprise model' for the delivery of infrastructure, by contrast to a 'transactional model' in an attempt to find a business model and value proposition that is more effective. They identify the integration of physical and

[26] http://www.p13.org.uk/

digital systems as key skills required for success. The use of models and visualisation tools for discussion and rehearsal enable exploration of options and value trade-offs. As well as describing their vision[27], they also propose steps to implementation in their 'commercial handbook'[28],

Although considerable work has been done in exploring business models for service ecosystems in cities (Visnjic et al., 2016), there remains plenty still to do: to understand the value of such ecosystems, to identify how it might be quantified, targeted and captured and, especially to build the capability to better use data in pursuit of those aims. The potential is oft quoted for data and information, along with digitalisation, to open up new sources of value, but the reality of moving beyond benefits from cost, materials and time savings is quite challenging. The FOuNTAIN Network concluded that there is a need for the UK to develop, 'the capability systematically to identify and derive business value (including political, technological, social, economic and environmental value) from Information Management' (FOuNTAIN, section 6). Their specific suggestion is to explore value-driven process models.

Value may also be obtained through using data to improve certainty, thereby reducing risk and thus enhancing the investment potential of a new asset or service, be it in financing or insurance. Turner Harris highlight the potential to build upon the BIM foundation to create tools to calculate whole-life value and to develop common models for lifetime value that can be used at all stages of the project (TH, p. 18). Risk reduction is offered by improved cost estimation, by better co-ordination of the value chain and the interaction of participants and by pursuing better assurance of outcomes. CAR (CAR, p. 32) notes the lack of data and of cost-benefit models for BIM applied to existing buildings and suggest that work here is essential to underpin debate about available value. This approach might be augmented by real-time reporting of asset utilisation (TH, p. 38), maybe by reference to digital twins, and thus a much tighter management loop that focuses on ROI. Quantifying benefits will be difficult and guidance, along the lines of the BIM Level 2 Benefit Assessment (PricewaterhouseCoopers, 2018) will be essential.

It is important to define a baseline for the exploration of the value to be derived from digitalisation (RALW). This is the opportunity cost of doing nothing proactive to leverage digitalisation for value – tangible or not (PricewaterhouseCoopers LLP, 2018, p. 24). It is almost certainly not zero. More important, though, is how to capture and monetise such new sources of value as a just reward for investment risk. This is so critical that it is discussed as a specific capability below.

It is challenging to align cost and investment with value created, especially in the different time scales of long-lived assets and services. Some investments in digital built Britain will depend upon platforms and upon network effects; unless a critical mass of users, subscribers or paying customers is achieved then the initial investment is never recovered, and the commercial model fails. This is one problem faced by demonstrator projects (van Winden & van den Buuse, 2017) and should be borne in mind when reviewing the business case for early experiments, and considering their implications for corporate value and investability.

This section will explore the following sub-capabilities that are needed to underpin corporate value:

[27] http://www.p13.org.uk/wp-content/uploads/2018/06/P13-Blueprint-Web.pdf
[28] http://www.p13.org.uk/wp-content/uploads/2018/06/P13-Commercial-Handbook-Web.pdf

- To discern multiple sources of added and accessible value and develop compelling models of whole-life value and totex (V3.1)
- To find ways to extract value and allocate reward to providers for value creation / cost reduction which is offset in time and space (V3.2)
- To understand and adopt appropriate digital tools and technologies in a timely and competent manner (V3.3)
- To predict and manage the ways in which sector capabilities enabled by digitalisation will support national and international competitiveness (V3.4)

V3.1 Discern multiple sources of added and accessible value and develop compelling models of whole-life value and totex

The nature and magnitude of benefits available depends upon the breadth of timescales and interest. The vision for digital built Britain emphasises the whole-life perspective and total expenditure (totex) incurred. While this applies to the 'system' as a whole, and hence to the UK at large, it is not clear that such considerations apply to each of the vast majority of companies participating in the sector now or in the future. We need, therefore, to be able to identify value that can be created and then captured by individual corporates from better use of digitalisation, data and information in the creation and operation of services and assets for best effect though-life. This capability is mirrored in the parallel sections in SERVICES and in the BUILT ENVIRONMENT.

Added value can be considered within the following areas:

- The built assets
- The services embedded in and delivered though the built assets
- Intangible benefits
- Process benefits
- The value of virtual assets composed of data, information and models
- Business models

Each of these have different implications for business models, their development and use.

i) Built Assets and digitalisation

The starting point is a shift of mind-set from simply managing assets to considering much more fundamentally how assets contribute value to an enterprise. The Institute for Asset Management (2018) discusses the journey from a reactive mode, where assets are seen as a source of problems and costs, to proactive management of the asset, from its very conception, through-life, for value. They emphasise the contribution of good data and information throughout, and provide an overview of the asset management landscape (Global Forum on Maintenance & Asset Management, 2014). Here the creation and capture of value are common. The BIM Benefits Measurement Methodology

(BMM)[29], commissioned by CDBB, highlights several benefit mechanisms that can underpin the creation and capture of value from built assets. The focus here is on savings in cost, time and materials, plus the impact on health and safety, project risk, asset utilisation, asset quality and reputation, all enabled through better data and models.

Another set of value drivers are the considerations of through-life benefits and costs, for example the through-life sustainability in refurbishment. There is continuing work that holds out promise for companies to access value at the end of their assets' lives by applying the concept of the 'circular economy' to the AECO sectors. This has been explored and modelled in the context of healthcare and hospitals, highlighting the wins available from refurbishment as well as in initial build, but emphasising that value is crucially dependent upon the availability of as-built data and information about the current reality of the fabric of the infrastructure (Wilson, Kishk, & Laing, 2013). Tracking the provenance of materials and components would inform end-of-life value so that built assets reaching the end of their service lives are more likely to be reused or recycled than the default option of being sent to landfill as waste (CAR, p. 8) and this thinking should be extended to other applications.

The benefits discussed above depend upon the digitalisation of the assets and the processes by which they are developed and managed. The benefits are either absent or much harder to access when the majority of the asset base is not digitalised. The lack of a common basis, therefore, undermines each of the components of any business case. This is true for each organisation with a portfolio of 'digital' and 'pre-digital' assets and also for the nation as a whole. As Turner Harris argues, 'the decision to digitise legacy assets or not is a product not born purely of cost and technology readiness, but also of long-term strategic positioning' (TH, p. 29). In general, there is much to be done to explore, demonstrate and persuade about the value of digitalising of legacy built assets and the development of tools to support the management of legacy built assets.

ii) Services, the built environment and digitalisation

This topic is considered more broadly and deeply within SERVICES, which explores the interaction between services and assets and the creation and capture of value, but one implication of success in this clarification of outcomes and on the activities that will lead to desired outcomes will be the potential emergence of supply chains which are focused on and aligned on delivering those outcomes. The development and management of such supply chains will be a key enabler for digital built Britain. The underpinnings for this are explored by Urban Innovation Labs (UIL a, p. 83) in the section on supply chain alignment.

iii) Intangibles

There are, of course, sources of value that may be pursued other than financial growth. For example, social value can be disseminated out across the community from the entire supply chain

[29] https://www.cdbb.cam.ac.uk/news/2018JuneBIMBenefits

through all stages of the asset's lifecycle (Supply Chain Sustainability School, 2017). This is potentially significant when supply chains involve local SMEs (Burke & King, 2015). There is continuing debate about the potential to add social value (see the discussion on defining benefits and outcomes in V1), and it is clear that companies will need assistance to discern, to create and to see a return from social value. Organisations such as Social Value UK[30] provide clarification of the benefits of creating social value and B Corps is an early entrant into certifying and legitimising corporate claims to social and environmental responsibility[31], but the capability for the typical UK company to account for and embrace social value is still only embryonic.

Nurturing and development of the natural environment, together with the green agenda, is undoubtedly a potential source of value from digitalisation. However, despite the guidance available for the financial sector and investors (Bosteels & Ulterino, 2018), there is little insight yet available on the impact of digitalisation *per se* on creating and capturing such value, for example from ecosystem services.

Risk management, especially around investment risk and its minimisation, is also a promising source of value. Turner Harris advocates the idea of 'BIM for investment' using data and models of assets, services and business models to identify ways to enhance the confidence in both revenues and costs and the use of through-life value models to underpin both funding and underwriting (TH, p. 19). Urban Innovation Labs points out that the benefits of better modelling and therefore more explicit management of liability through the entire supply chain offers leverage for all involved (UIL a).

Yet other sources of value include the emergent and system intangibles such as resilience. This has been explored specifically with a view to clarifying the return on investment (Hall et al., 2017). The domain is ripe for further work, not only in characterising different contributors to resilience, but also in valuing the contributions, framing the opportunities and establishing metrics to open up options to classify and capture such value (see also the discussion of complex projects in G4).

iv) Process benefits

Digitalisation offers promising development opportunities for organisational processes, both within and between organisations (SW – Systems). This is further addressed in Data, information and models (D1.2). Typically, work in modelling such processes within the context of evolving BIM has a long way to go, with future directions identified by Shah et al. (2018).

Process models provide one explicit approach to exploring how value is created and how data and information are used across the sequence of activities within a supply chain. The mapping of such models is espoused by both the FOuNTAIN Network and the DFTG Roadmap Working Group. Indeed, the FOuNTAIN Network describes one of the key capabilities required: 'the capability systematically to identify and derive business value (including political, technological, social, economic and environmental value) from Information Management. Specifically, a value-driven process model is required' (FOuNTAIN). The DFTG flags up the need to understand industry

[30] http://www.socialvalueuk.org/
[31] http://bcorporation.net/

reference process models in order to clarify the role of data and information sharing in creating and capturing value.[32]

Other sectors have transformed the performance of their supply chains using process redesign in the context of digitalisation, suggesting there are lessons to be learned and opportunities to be grasped (see Sector perspectives).

v) The value of virtual assets composed of data, information and models

Companies will need to think not only about the ways in which services and their built asset resources can be augmented by data and information to create value, but also about data and information as assets in their own right, each capable of being mindfully managed to deliver yet further value. Highlighted in CDBB consultation workshops (RALW, p. 26; SW – Data; SW – Information), this capability is also identified within the DFTG Roadmap[33] as that of companies having the ability to identify metrics for data and therefore treat data as an asset to be managed for its value creation potential.

A review of the literature (CAR, p. 17) reveals a lack of awareness of the value that can be generated by digitalised facilities management, together with limited understanding of what information can and should be transferred between stakeholders through the life of the built asset.

vi) Business models

New business models are often held out as a panacea for deriving value from digitalisation. However, in the abstract this is less than helpful. Identifying and then accessing new sources of value is difficult. Similarly, it is difficult to identify the most important elements and structure of candidate business models. In this, as in many other areas, any guidance that is created in order to help companies built this capability must avoid being so generic as to be useless and avoid merely reporting an isolated instance. The most helpful guidance must be at the right level (CAR, p. 27). Access to a framework or taxonomy of candidate business models, together with guidance about their strengths and weaknesses would provide maps for businesses exploring the potential uptake of digitalisation, but the initial inspiration cannot be manufactured.

Many articles espouse the potential for businesses to exploit the opportunities within smart cities, but there is no framework that assists people to navigate the hype and the recounted experience and insights in ways that steer them to relevant information about their concerns. Hence, there is potentially much to be learned from the experience gained from smart city pilots and demonstrators, but if businesses are to develop the capability to find business model opportunities, they will need maps and guidance through the lessons and caveats already learned.

[32] Task 3.2 in the DFTG Roadmap (Enzer et al., 2019)
[33] Task 2.3 in the DFTG Roadmap (*ibid.*)

Considerable work has been done on business models that focus on sustainability (Abuzeinab & Arif, 2014), through-life environmental impacts and on renovation projects (Holopainen, 2016), motivated primarily by an enthusiasm to improve environmental performance. This same work is also valuable as a source of ideas and of guidance for companies seeking inspiration to design new business models. Researchers in Germany have considered tools to review business models within the SME supply chain (Schüle et al., 2016), but there is still clearly much to do in the UK.

With lack of awareness of the benefits of digital tools applied to through life management being flagged up as one of the significant barriers to adoption (CAR, p. 26), there is a clear case for well-targeted and designed case-studies and demonstrators. Construction of new assets increases the total value of UK infrastructure by just 0.5% a year, as illustrated by CSIC (Bower et al., 2018). Therefore, it is vital to develop ways to capture value from the legacy assets that make up most of the built environment.

Developing confident predictions of likely returns and their timing and of the necessary investments is fundamental to investment decisions. This can be supported by models. An important capability is to create such models at a level of granularity and credibility that they will underpin investment decisions. For many, creating the structure and the robust data to populate such models will entail building new capabilities and new sources of information. Work has been done in creating foundations for such modelling (PricewaterhouseCoopers, 2018) but the task of discerning value exchange between stakeholders throughout the supply chain is at an early stage, with promising early examples of mapping and evaluation (Zheng et al., 2019). Clearly, there is much more to be done in order to understand and then justify value exchange for whole projects and across supply ecosystems.

Companies will need to find applicable and robust data for their virtual models. Considerable work here provides both process and examples (Infrastructure and Projects Authority, 2011a; 2011b; PwC, 2018). The allocation of benefits derived to causal factors via the creation of a robust business model will be of key interest to companies planning to invest in digitalisation, especially considering the extended supply chain. Companies are very likely to require help with discerning, articulating and evaluating these benefits and how they can be accessed. This will be vital to support any enthusiasm for investment.

Modelling the whole-life value of assets is complex, but digitalisation presents opportunities both for better models and to change the game, all with the aim of achieving value.

V3.2 Find ways to extract value and allocate reward to providers for value creation / cost reduction which is offset in time and space

As discussed above, the payoff for investment in digitalisation may come much later than the next quarterly earnings statement. Companies and the people within them who make decisions are, generally, rewarded for returns or the prospect of returns that are near at hand and clearly accessible. Cashflow and annual (or quarterly) profits are determinants of corporate health and career success. Hence, for all that the UK at large may benefit from investments made today that will help others, either many years from now or in very different places in the service / asset ecosystem, it is not at all clear how to make such benefits available to the companies that have to invest today and to credit the people who decide to pursue such altruism.

The capability to identify value created elsewhere is vital, as is the ability to recognise and reward appropriately the best system-wide decisions made by people who may not see those benefits. It is not at all clear how this capability can be created in practice. Furthermore, this is a capability of high leverage because it will enable investment that cannot today be commercially justified.

It is easier for the public sector, with its mandate for social benefit, to justify investments in digitalisation for improved performance. NHS Digital is investing its Long Term Plan (National Health Service, 2019) to provide digitally enabled health services as default. Their plan includes short-term rewards for local services digitalising, e.g. by facilitating access to system data that will enable service providers to make better decisions (NHS Digital, 2019a) and by discounting the cost of access to cloud services (NHS Digital, 2019b). The long-term goal of better outcomes for patients is compelling enough to drive the NHS to invest, showing the importance of a clear, unified vision in making the case for long-term investments.

However, even without a singular vision there are ways to reward investment. The iBUILD research project[34] sought to make digitally enabled infrastructure appear more investable by providing more quantified evidence of the value of digitalisation to the sector. In their conclusions, they emphasise the need for a framework that helps maximise return on investment by ensuring growth is fairly distributed across regions; that enshrines whole-life benefits in the initial valuation[35]; and that accelerates uptake through comparative demonstrators.

Routes into this capability may entail sophisticated business models explicitly shared between collaborators which reflects an agreed picture of cause and effect in the creation of value, and which then underpins mechanisms to allocate recompense and reward for creating value that is not in the same timeframe as the investment and expenditure. This is, of course, an issue faced by regulated capital-intensive monopolies and it is likely that experience and insight from those domains, for example in computer models and decision support tools, are likely to be very relevant and transferable.

Consultancy firms such as PricewaterhouseCoopers (Hirji & Geddes, 2016) and Ernst & Young (2018) are exploring the conflict between short-term pressure and long-term investment, both arguing for the need for innovative metrics that clearly capture new types of value, some of which can be captured short term. EY's long term value reporting framework helps organisations express whole-life value to stakeholders, thus clarifying the reasons for investing. However, short-term incentives to encourage the most reluctant are less well-explored than frameworks and metrics in the literature, despite increasing pressure to demonstrate a strong financial performance within two years of investment (Ernst & Young, 2018, p. 3).

[34] http://gtr.ukri.org/projects?ref=EP%2FK012398%2F1

[35] *ibid*. recommendation 10 notes that new forms of investment and revenue streams are needed in order to realise this value.

In the case of infrastructure assets characterised by long lives, there will arise the need to identify the sources of value on a vast time scale, and not just the efficiency and effectiveness of the assets through-life. Here, too, there is much that has been done to create auditable and repeatable approaches to describing such value, for example Srninvasan and Parlikad (2017).

The issues will, of course, ripple down the supply chain. For example, there needs to be a translation into processes, data flows and interfaces, mutual responsibility and expectations that will enable the several organisations in any supply chain to create the benefits from services and from built assets. This capability was flagged up within the early scoping workshop (SW – Supply Chain) as a key enabler of digital built Britain.

The ability to craft contracts to underpin working relationships, mutual expectations and obligations becomes an important capability when costs and benefits accrue to different parties at different times. Challenges include finding ways to adequately articulate and specify the contracted requirements and obligations (G3) in each of these dimensions. The potential role of digital twins in designing future operations and then in monitoring and managing those operations could then be explored and extended to the role of digital twins in informing contractual negotiation and management. Implementation will entail translating the business models into contracts, into organisational forms, into processes and into supply chain management tools.

This capability is obviously tightly linked with those above, but also links across to capabilities elsewhere in the framework:

- In defining data and information, both as sets and streams (D4),
- In the GOVERNANCE framework that is generally applicable to the domain
- To complex and integrated systems (G4) where the magnitude and likelihood of interlinked events and their consequences may influence contractual structures
- And to the adaptability of companies as the ecosystem evolves.

There are major unexplored issues in this area, and it would benefit from both research and practical demonstrators to make a compelling case for investment.

V3.3 Understand and adopt appropriate digital tools and technologies in a timely and competent manner

Digitalisation is often hailed for its ability to offer new sources of value through the imaginative use of data and information applied to traditional industries. Articles about this phenomenon cite early adopters or exponents of the new opportunities (e.g. Ernst & Young, 2011), especially new entrants into their sector, for example Nest in home energy monitoring (Mooney, 2016) and WeWork in corporate real estate (Turk, 2018). Navigating through these anecdotes does not make it easy for a company to identify exactly which digital tools might be of greatest use, how best to use data and information, or what data and information might be cost-effectively available and also a source of value. This is complicated by the many interfaces between companies working in the built environment, and will become yet more complicated through the integration of services at the core of digital built Britain.

The IET provides a table of considerations in the adoption of digital tools and technologies (Barnaghi, 2019). This covers topics such as needs and consents, ethics and security, monetisation, data considerations as well as the engineering and technology involved. It goes on to reference the organisational and change management implications.

Even after identifying the right tools, adoption is not always straightforward (see the section on barriers to adoption, L1). Turner Harris identified ten primary barriers (TH, pp. 16-17) to the adoption of digital tools while CAR surveyed reasons for and against the uptake of new technologies (CAR, pp. 63-64). Primary barriers were identified as cost-benefit and uncertainty on return on investment, which link to the points above about perceptions of value. Another key barrier is the lack of necessary skills for implementation. Primary enablers include cost-benefit analysis, personal recommendation and, notably, an explicit client requirement. This supports observations about the effectiveness of the BIM mandate in driving the uptake of that technology.

A survey of the grey literature confirms the significance of initial cost as a barrier (CAR, p. 27). Concerns about the costs of training augment this barrier. Interestingly, lack of client buy-in is an important blocker to the uptake of technologies for the construction and design and planning phases among SMEs and is also particularly an issue in the operational life-stage (CAR, p. 26). Establishing what guidance would be effective and then creating such guidance seems critical to accelerating uptake of new technologies and then maximising adoption across the sector.

Several commentators suggest that there will be great value in the emergence of platforms (CAR, p. 8) or of systems that offer bases for sharing data and thus, implicitly, accelerating the adoption of new approaches and tools with respect to data and information. Indeed, platforms could well disrupt the supply chains, especially among SMEs (Laine et al., 2017), leading to new avenues for value creation and renewed anxieties about where value will be realised. There is a debate about whether platform development is best provided by the natural emergence of market provision, but certainly such an evolution will depend upon standards and assurance associated with the sharing of data. Note specifically that the Digital Framework Task Group sees the evolution of national digital twins as being independent of platforms (Bolton et al., 2018).

Analogous to the issues around discerning value there are problems with guidance available to companies in the uptake of technology (CAR, p. 27). This seen in documents that either espouse generalities or, perhaps inevitably, are very application specific, describing post-event a particular implementation. Hence, companies in digital built Britain will need held developing this capability, for example via the following:

- Evolution of a classification schema for the target companies (SW – Stakeholders), the application domains, use cases (e.g. TH, p. 8) and tools in order to make the lessons from early adopters more generalisable.
- Guidance in the analysis and prediction of advantages/benefits and disadvantages - for different groups of stakeholders who will be subject to different industry processes that may, of themselves, constrain or accelerate adoption.

- Creation of an evidence base of use cases and the generalisation of lessons from demonstrators and pilot projects. Note that these lessons need to be pitched at the right level, with CAR (CAR, pp. 27-28) noting that current guidance is too shallow, and it is difficult for users to confirm the applicability of a given technology.
- Descriptions of adoption pathways and barriers to avoid the common sources of failure.
- Adopting social science perspectives (e.g. Shojaei a, b) to gain insights into the dynamics of adoption, especially where digitalisation may change the strategies, resources, approaches and the power balance of actors in the sector.

V3.4 Predict and manage the ways in which sector capabilities enabled by digitalisation will support national and international competitiveness

Digitalisation will change the bases of competition both nationally and internationally, and policymakers and decision-makers will need to understand this in time to act. This understanding will be supported by explicit exploration of the issues, and perhaps by appropriate modelling of sector investment, profitability and performance (RALW, p. 26).

As well as the domestic agenda, companies will need to develop their competitive position, both for those that wish to operate abroad and those that wish to respond to foreign competition. This is likely to be complicated by the potential for new approaches and new technologies to fundamentally change the nature of competition in the UK. For example, off-site manufacture (OSM) could open the sector to new participants and could change the equation about which companies can operate in which geographic scope. Similarly, the spread of tools and techniques to make better use of data could significantly reshape the competitive landscape. Scenarios for the future are not necessarily always rosy and the interactions not always positive (Harty et al., 2007).

Companies will therefore need to understand the likely impact of these changes, to understand the implications for their businesses, those of their partners and take appropriate actions. While there is much comment on changes in the levers for general industry competitiveness (for just one typical example see Wynn, 2018), it is a major task to move toward a carefully crafted and robust plan with appropriate investment. The capability to develop the picture and the plans to compete in a new and evolving world will be key to success. It is not clear that the 'long tail' of small companies currently have this capability. They are likely to need help discerning and characterising the opportunities and threats, translating these into likely opportunities the threats for their specific businesses and crafting appropriate strategies.

This section has explored how attaining value from the built environment and services begins with identifying what outcomes are desired; translating 'hard' and 'soft' outcomes, mental and business models into computer models; and bringing in stakeholder perspectives. This vast quantity of information can be usefully sorted by organisational frameworks and technological tools to help provide insights, which can then be transformed into specifications for procuring the assets and services themselves. Finally, new business models and new ways of thinking are required to integrate services and the built environment in ways that create social and environmental value for the public, as well as financial value for those that invest in digital built Britain. Digital technology, data, information and models are not inherently valuable, however, and we require mechanisms such as decision and evaluation frameworks to ensure that we are using them to make better decisions.

SERVICES: Develop and manage services integrated with and delivered through the built environment

The introduction below provides an overview of the **Services** category of the Capability Framework for creating a digital built Britain.

Click here for an introduction to the **Capability Framework** as a whole, including links to all the categories involved.

Services capabilities

Develop and manage services integrated into the built environment

- Discern and define the value and outcomes from services that depend on built assets (S1)
- Identify and define interactions and 'causality' between services and assets which underpin specification, creation and management of both (S2)
- Develop and manage services integrated with and delivered through the built environment to deliver value for users and investors (S3)

Introduction

Digitalisation, and the data it produces, will profoundly change the way that services are delivered, potentially enabling services and assets to work in a more integrated and effective way so that they can be managed together. It will also change the way that users and service providers interact with the built environment and the organisations that manage it.

We need to be able to define the value we want from services that are embedded in, or delivered through, the built environment. This is not easy, and research is needed to arrive at consistent and comparable ways of defining and measuring service performance. It is important to focus on what stakeholders value, rather than on what is easy to measure. How can digital tools help here? Can we obtain different kinds of data and how do we preserve privacy? How will the digitally disadvantaged cope in this world? Will the elderly, those with disabilities and homeless people be unintentionally excluded from the services of digital built Britain?

We need to understand the interplay of cause and effect between services and the assets that underpin them. This understanding will help us make more targeted decisions about investments and interventions. We also need to investigate how the engineering and design of our built environment can enable new and better services, and how digitalisation can support this.

We need to be able to recognise and allow for any dependencies that might be created. If a data stream from the infrastructure fails can we maintain the dependent services? Will there be ripple effects that will bring a city to a standstill and endanger the public?

Finally, we need to design and manage the services and assets in order to exploit linkages between them and deliver the benefits we want cost effectively. A key part of this service design will be to build business models that reflect the value created by services, the load they place on buildings and infrastructure – and the cost of failure, should it happen. We need tools that model these relationships and simulate the outcomes from decisions, so we can optimise the investment in services. How do we model the capital cost of the assets, and the lifetime value of a better service, in order to decide who pays for what? What data can we gather that will enable us to manage the assets, the services and the interplay between them, swiftly and effectively?

Today, the UK generates about 80% of its GDP from the service sector, of which about half is dependent on the built environment (UIL b, p. 2), and many of the benefits that accrue to the people of Britain in the coming decades will arise from services that are embedded in or delivered through the built environment. However, within the services sector, the top 25% of businesses in each sub-sector are approximately 2 to 5 times more productive than the bottom 25%, and productivity is falling (HM Government, 2018b). Digitalisation will profoundly change the way that services are delivered, potentially for the better. It will also change the way that services, their users and providers interact with the built environment and its management organisations. The trend to ever greater integration will also be seen in services and between services and their supporting asset base. What capabilities are needed to maximise productivity in digital built Britain?

The following section explores, specifically, the new capabilities that the UK will need as a result of the interaction of services and the built environment, the trend to integration and, above all, increasing digitalisation. It draws upon commissioned work, especially that of UIL (UIL b, p. 2), and upon the workshops and networks from the past 18 months.

All of these capabilities will need to evolve as requirements change, as the surrounding context evolves and as the underlying technological opportunities from digitalisation continue to emerge and flower.

An exemplary project in recent years that explored the interface between services and the built environment was The Health and Care Infrastructure Research and Innovation Centre[36], which grew between 2006 and 2014 to become the world's largest research programme on the relationship between healthcare, infrastructure, technology and services. The team focused on the complex relationships between healthcare infrastructure, technology and services, 'important because the mismatched timescales between technological innovation, changes in service delivery models and fixed capital infrastructure investment make it hard to anticipate and plan for future needs, and manage the change processes'. They also explored the impact of innovations in healthcare infrastructure.

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[36] http://www.haciric.org/

Their final report (HaCIRIC, 2014) covered key topics pertinent to digital built Britain and, by analogy, such work seems an encouraging prototype for future research in this space:

- The international dimension of healthcare infrastructure provision
- Decision support to achieve better health through better infrastructure (HaCIRIC, 2011)
- 'Bundling' together infrastructure and clinical services to align risks and incentives
- Design for flexibility and implementation of practice-based commissioning, respecting local priorities
- Assemble, collate and critically compare the evidence-based design guidance and tools and strengthen the quality and safety agenda in infrastructure design
- Open scenario planning approach to help develop infrastructure solutions that could suit a number of different future scenarios
- Longitudinal analysis of the impact of design and operational practice alternatives
- Use of simulation tools to identify the realisation of benefits (Yates et al., 2019), especially from non-economic perspectives.

These insights signpost the potential for similar research projects.

S1 Discern and define value and outcomes from services that depend on built assets

This capability is analogous to that of defining value across the wider digital built Britain (V1), but highlighted here are several issues that are specific to services. UIL note that, although there established bodies of knowledge in this domain there remains work to be done to 'establish the value of the technical, social, economic and environmental causal relationships between service outcomes and the underlying infrastructure' (UIL b).

First, this document discusses of capabilities in defining and deciding the outcomes sought, and exploring tools that may assist. While the rest of the document assumes that digital built Britain will strive to meet all the demand for services, the question of whether demand management has a role to play and, if so, how digitalisation might affect it, is picked up here. Finally, there is a discussion about the need for continual development of services to respond to, and perhaps shape the expectations of people exposed to the continuing stimulation of greater digitalisation of all aspects of living.

This document artificially separates the capability to clearly define the outcomes needed from the services from the capabilities to design and develop services (S3). Defining benefits, needs and outcomes is more generalised and less situation-specific, whereas the design and development will depend upon the available infrastructure, the service delivery partners, and the data landscape. Furthermore, often those commissioning services will be different people in different organisations from those engaged in delivery. The capabilities are tightly linked, but they are separated here for emphasis.

This capability must be supported by the following:

- Discern and define the outcomes and value sought from services delivered in and through built assets (S1.1)
- Deploy demand management as part of the portfolio of options in debating and managing outcomes (S1.2)
- Forecast and pre-empt market dynamics and user behaviours in the face of digitalisation and integration (S1.3)

S1.1 Discern and define the outcomes and value sought from services delivered in and through built assets

Reflecting all that is discussed in section V1 on defining benefits and outcomes, a key starting point is the ability to decide what is valuable and what to prioritise, within and across the rich portfolio of services delivered though the built environment. Analogously, policymakers, decision-makers and stakeholders need to clarify the outcomes they seek and how services will deliver those outcomes, subject to what compromises and trade-offs. UIL define a key capability here as the ability to, 'Define service outcomes, capability and capacity, linked to the elements of the infrastructure and service required' (UIL a, p. 78). Even the Home Office offers advice along these lines (Tarling, 2017).

Some of this might be achieved through a translation from the overall outcomes sought (V1) to an articulation of the outcomes sought from services[37]. However, there is little research into methods to describe and define service outcomes, and especially their decomposition to determine what is needed to achieve the outcome at varying degrees of abstraction (UIL b, section 3.2).

In particular, the articulation of value, both by the public sector for citizens of the UK and by private institutions for their investors and other stakeholders, needs to encompass both the service and the asset; for example how the value embodied in the asset translates into value in the service, how 'costs' incurred in the asset may be better viewed as an 'investment' in the service, how the attributes valued by users are actually a result of investments made elsewhere. This is analogous to the points made in the discussion of business models and the capacity of the investors to see a return (V3).

The role of Service Dominant Logic as a way of exploring the value of services is well established and it together with other models are described by UIL (UIL a), but it is not clear that 'value in use' has yet been fully understood with respect to assets in support of services. Research here would be valuable to extend and integrate the concepts and tools.

This will be closely linked to the approaches used to design the service itself. Business Process Simulation is well established with a range of supporting simulation tools (Jansen-Vullers & Netjes, 2006). Considerable work has been done modelling the interaction of business processes and IT systems, but there remain challenges in further developing the tools. This is, however, outside the current scope, where the focus is on accessing and using such tools.

[37] See UIL a for more detailed discussion of this point and for specific instances drawn from road transport and energy sectors.

Many practitioners design 'journeys' or 'storyboards' in-service design. They are valuable in assessing key touchpoints, enablers and blockers to performance and the implications of digitalisation. UIL (UIL 6) provide an example and illustrate its use.

Such use cases can be interrogated with both explicit frameworks (such as process maps) and with service system models. Computer models of the built assets could be valuable tools in exploring the different operating conditions under which services will be provided. Pedestrian simulations, for example, can be conducted using iterations of an asset, exploring different configuration, planning maintenance and so on.

There is also the need to track the 'information pathways' between asset state and performance, service state and performance, and outcome. This is an important step, incomplete today and needs work (UIL 3).

It is important that the people of digital built Britain develop a language and a fluency in the description of services and their characteristics that enable the delivery of valuable outcomes. One starting point is proposed by UIL (UIL 3), suggesting that 'capability', 'capacity', 'state' and 'quality of service' be regarded as key descriptors of a service and its ability to deliver an outcome. Thinking tools of this nature will be essential to underpin the UK's ability to negotiate outcomes and value.

Frameworks exist for looking at the interface between services and assets. Typically applied to 'smart cities', there is a recognised need to develop them to account for the dynamics of human behaviour in buildings and cities (Al Sayed et al., 2015). Some emphasise the importance of systems thinking (Al-Sayed, 1991), while others explore interactions.

One example of a framework that addresses the gap identified by UIL and explicitly supports the clarification of links between services, assets and enabling data can be found in Heaton and Parlikad (2019). They illustrate the silos of the traditional operating model around services based on and embedded in assets, with the disbenefits of different data management regimes mitigating against cross-silo collaboration and against integrated services. They discuss the approach and attributes of several of the smart city frameworks, distinguishing theirs as linking citizens' requirements and the city's functional outputs of the city's assets. Importantly, they illustrate the mutual dependencies between assets in support of a given outcome, and show how data integration can glue together the management of the component assets in support of a service. The creation and development of frameworks like this offer a means of tracking from outcomes and benefits to enabling infrastructure. It may be indicative of a way forward in tools to support this key capability.

Temporal and spatial scope matter here too. EU studies such as (ESPON, 2017) show the benefit of digitalisation of public services in cities, but illustrate the wide variation of uptake by region. Looking out over longer timescales, what services are provided by the natural environment and how does investment and management of the built environment support or damage such services? What investments made today will underpin services into the future? How should these be valued today? Could Joseph Bazalgette manage to sell his famous sewerage infrastructure in London under today's perceptions of value? Has the UK the capability today to pursue long-term value? Will our grandchildren agree?

Value and outcomes arise from other intangible properties of the systems that may be created in order to underpin services from which value is derived. Security is one such property; both an outcome in its own right within each service and each asset, and as a sought property to be assured from interlinked systems. However, work done to characterise security and to make it discussable and negotiable within the debate about service outcomes would add further value to current guidance. Only when it is fully understood both generally and in specific contexts might it become possible to specify outcomes in this and other intangibles such as vulnerability, resilience and robustness of service outcomes.

This relates closely to the use by the citizens of digital built Britain of underlying technology platforms. For example, most users do not understand what their smartphones do, nor the privacy and security issues around them (Ferreira et al., 2015). If users do not understand these things then they are incapable of deciding, negotiating or verifying the trade-offs in, or balance of, outcomes that they seek. The same will be true of the use of post-occupancy surveillance and data collection in the built environment, no matter how well-intentioned is the service support proposition (CAR, p. 28).

The definition and negotiation of intangible aspects of service outcomes will become an important capability in a world with so many virtual attributes. A useful capability will be enabling service valuation by linking simulations of the service with simulation models of the asset. Furthermore, the governance and software toolset surrounding and enabling such simulations will be important enablers in assuring security and privacy with respect to services. This is discussed this further in DATA.

Because the customer is usually intimately involved at the 'touch point', additional consideration needs to be given to the matter of the interfaces between services and users, the opportunities this offers and the demands placed on both service design and user competence. Tools to assist in understanding the service user and their level of digital literacy and competence will be needed here (see also the discussion of the digital competency of the user in LEARNING).

As was emphasised in the discussion of measurement and performance indicators (V1.3), developing the capability to put metrics to outcomes and benefit is useful because it provides shared measures of performance and supports specifying, contracting, and managing services. More importantly, it helps clarify exactly what is being sought and how success would be recognised. Determining how service outcomes and underlying infrastructure can be measured is a critical component of the capabilities recommended by UIL (UIL b, p. 28).

S1.2 Deploy demand management as part of the portfolio of options in debating and managing outcomes

As part of the trade-offs to be made, one candidate activity that deserves attention is that of demand management. The benefits may be significant. UIL (UIL b, p. 24; UIL 3, section 5) note the significant impact in the power sector, suggesting that smart metering and demand response can lead to better matching of supply and demand and thus to reduced need for asset buildout. By analogy, the implications for the built environment may be considerable and deserve exploration in domains other than energy.

Digitalisation and ever more pervasive data and information may provide powerful levers here. It may be, for example, that the populace is willing to trade-off the potential loss of privacy from location tracking in exchange for information about accessibility to and availability of services. Of course, this occurs today when Google Maps uses location data to highlight road congestion and suggests alternative routes to a destination.

Demand modelling associated with the smart city is well-established in domains such as water and energy, (the basis of the smart meter debate) and in urban transport, for example in car sharing. These tools will be needed to underpin prediction of the system behaviours subject to any planned deployment of demand management initiatives.

However, the representation mechanisms of the UK populace at large need to begin to develop the capability to decide the value of such services and the price worth paying. This will depend upon combining visions of the future, clarity about enabling requirements or outcome implications, systems thinking and then the tools to support discussion and decision. There is work to be done here to decide the nature of, then to design and to integrate, demand management capabilities into the portfolio.

S1.3 Forecast and pre-empt market dynamics and user behaviours in the face of digitalisation and integration

Citizens are continually being educated in the art of the possible in the digital sphere as consumer devices and internet-enabled services flourish. Expectations about user interfaces and about service performance levels are set and develop with every new service and product launch. Indeed, consumers have expectations to which providers in competitive markets have to respond in order to succeed (TH, p. 14). The ability to 'get ahead of the curve', highlighted in a CDBB consultation workshops (RALW, p. 9), is as important in services as in other aspects of digital built Britain, as discussed in section V2. In the service domain other trends will also be important. Contextual drivers (see CONTEXT) such as the rise of the 'experience economy' and the 'sharing economy' will condition the changing wants and needs of the populace, and this will happen differently across different cohorts.

S2 Define an architecture of 'causality' between assets / infrastructure and the dependent and provided services which can underpin specification, creation and management of service

This section builds upon the recommendation from UIL (UIL a, section 4) (UIL b, section 4) that one of the prime capabilities needed is an understanding and definition of the causal relationships between service outcomes and the underlying technical, social, economic and environmental infrastructure. These are unpacked as a set of sub-capabilities and explore each. The focus here is on the digital aspects of services but there are of course, many other sources of interaction, for example the impact of the quality of buildings on morale and teaching in education (UIL a, section 2.1) and via many of the benefit mechanisms explored in the section about defining value (V1) within digital built Britain.

Note the relationship of this capability with that of working across the interfaces between complex and integrated systems (G4).

There are two sub-capabilities discussed here:

- Identify the coupling between activity and value (through asset lifecycle) for the interaction of i) services and assets and ii) services and networks (S2.1)
- Understand and predict the interdependency and behaviours between different services at different spatial and temporal scales (S2.2)

S2.1 Identify the coupling between activity and value (through asset lifecycle) for the interaction of i) services and assets and ii) services and networks

The section above discusses the link between assets and services, between interacting services, and between assets, services and the data that supports the management of both. It is essential that these linkages be understood and that the tools and insights exist to allow all involved to engage with the inevitable interactions between the creation and management of services and the concomitant creation and management of assets and of data and information.

The capability to understand and define the causal links between parts of the service-asset system will need both profound thinking to discern the subtle and extensive linkages (highlighted in SW – Services), and also the means to make this accessible to a very wide range of stakeholders. Today, the effect of asset characteristics upon associated services is not well understood (UIL b, section 3.3.1). Only if the citizens of the UK fully understand how and why an investment in asset 'A' leads to an improvement in service 'B' will they be equipped to meaningfully comment on expenditure and returns. Only if operational managers understand the causal links will they be able to make the right decisions and to intervene as and when needed, in time.

Indeed, the entire dynamic of the service and its supply chain, be it targeted on efficiency, responsiveness or resilience, will profoundly affect the nature of the coupling between service and assets (UIL b, p. 44 and section 3.3.4).

Understanding the architecture of linkages and the interplay will involve:

- Understanding 'cause and effect', while recognising that it is not simple nor linear but more likely to be loops of interaction with many feedback loops and interdependencies
- Discerning the cross-coupling between nominally adjacent systems

- Recognising where interdependencies may be sources of synergies and robustness or instead give rise to risks and vulnerabilities[38]
- Understanding the emergent properties of systems, such as security, vulnerability, and resilience
- Exploring the dynamics of the linkages and the interplay – how are they affected as the assets change over life or if the assets have different configurations.

The whole issue of 'tight' versus 'loose' coupling between services and assets is explored in depth by UIL, both in their review of the literature (UIL b, p. 72) and in their exploration of recommendations (*ibid*., p. 72), and there they highlight some of the considerations and emphasise the significance of understanding such coupling.

Digitalisation will have a massive role to play here, both in supporting the definition of causal links – but also in establishing and maintaining such links. For example, data on asset condition, maybe from the emerging plethora of IoT sensors, will be translated into information about potential service performance.

Modelling is essential in this space[39] as a useful tool in this exploration of linkages and causality. Firstly, exercising the models (both static and dynamic) will offer better understanding and insights. Secondly, models of assets coupled to services will give emphasis to the interfaces so encouraging deeper thinking of how linkages may be made and will evolve. Thirdly, the use of modelling tools will encourage exploration of the assumptions and hypotheses that designers, of both services and assets, bring to the engagement between them. This explicit articulation and testing of mental models will be core to debating, understanding and then communicating the interplay and causality. The 'governance' element around models, considering decision rights, access permissions, and the processes which are to be used in managing the data and models will be fertile ground for interactions between services and data, and a source of both opportunities and threats.

Service systems are typically components of 'Systems of Systems' (UIL a, p. 72) and developing the capability should be informed by this whole area of research. Similarly, the systems domain, its modelling and its link to the modelling of built assets will be informed and assisted by the technologies, tools and mindsets of Model-Based Systems Engineering, which is discussed in more detail in DATA.

Interactions between adjacent and interacting service systems are a critical subject to be understood in depth. For example, as UIL note, today's failure of public and private stakeholders to work sufficiently closely together precludes the effective development of seamless and networked mobility ecosystems (UIL b, p. 11). They illustrate this further, highlighting the need for co-ordination between owners of fixed and mobile assets, managers of funding, data exchange and, of course, public transport authorities. Interactions span many scales, organisations and interests. The vision of connected autonomous vehicles illustrates the explosion in complexity across all interfaces, especially of data and information. As an example of the exploration of interactions (and of causality between elements of the system) UIL note the work of the Transport Catapult (2017) on 'Future

[39] For an exploration of current practice, see (UIL b, pp. 38-44).

Proofing Infrastructure for Connected and Automated Vehicles'. See also the work of (Prorok, 2018) into locating and managing sensors to optimise autonomous vehicle and other planning in the built environment. These are examples of the research needed to underpin the capability to understand and manage the interactions between services, built assets and data.

Attention must also be paid to emergent properties arising from the systemic linkages between assets, services and organisations. If asset performance underpins service performance, then how does the resilience of a network of assets affect the resilience of a portfolio of services? Only with a deep understanding of these interactions will it be possible to specify the performance requirements of the assets and of their accompanying data and information in order to assure delivery of services at the required levels of availability and resilience.

Note also the interactions via data and information. UIL discuss the importance of shared data and models, based on agreed common data environments, (UIL a, p. 57) alluding to the advantages of a 'single source of truth' and noting the dependency between service providers and infrastructure owners. This 'single source of truth' is the data and information at the very core of models used for service design and management and so becomes a source of interaction, for good or ill.

Networks of supply chains underpinning services create their own links and interactions which must be explicitly recognised and understood. Indeed, that the Office for National Statistics should map such chains and their value is a specific recommendation of the Blackett Report (HM Government, 2018b). Failures within the supply ecosystem have the potential to massively disrupt delivery of a range of services, both at a subtle level and more obviously as was so graphically demonstrated in the Lancaster floods of 2015 (Royal Academy of Engineering, IET, & Lancaster University, 2016).

All of the interactions discussed above are in addition to the inevitable interactions between the interplay of sectors in the wider sense, highlighted by UIL (UIL b, section 3.1.2).

With the capability to discern, characterise, describe and model these myriad and potentially subtle interactions, it becomes possible to better design the assets, the services, and the underpinning data and information. Operational processes can be designed, described and shared, knowing the key attributes sought, as well as the mutual needs and interdependencies of the various participants in the whole system.

This in turn will underpin the ability to develop indicators and measures of performance of assets, services and of the enabling processes. With this clarity it becomes possible to specify inputs and outputs and hence create contracts throughout the supply chain which ties together assets and data and the services which deliver benefits to the citizens and economy of the UK. Considerable work has been done in this area, especially in the context of smart cities (Bosch et al., 2017).

This capability links tightly to the mapping of 'industry processes', both to ensure that important elements are not omitted and also for the definition of key decision and thus of the data needs, as called for by Task 3.2 in the DFTG Roadmap (Enzer et al., 2019).

In building such architectures, practitioners will need to focus on the interfaces (user to system, system to system and organisation to organisation) (RALW, p. 24), because of the functional interdependencies across the interfaces, because of the data transfer interdependencies, and because that is where supply chain management will matter most.

Standards will have a key role to play, enabling or undermining, the ability to take advantage of the convergence of services and the built environment. Hence, there is a specific need for the creation of causal architectures to explicitly include an understanding of the interplay of standards (as recommended by UIL 5).

As the capability develops in the UK, so these cause and effect networks will be understood as ecosystems rather than supply chains because such thinking better reflects the cross-linking interplay which will inevitably emerge (UIL a, p. 57).

S2.2 Understand and predict the interdependency and behaviours between different services at different spatial and temporal scales

Spatial scale matters deeply to the question of interdependency. The behaviours will be very different depending upon the spatial scope, be it across a single building, a city block or at a larger scale. The need to build capabilities in modelling and understanding different scales and the interactions between scales, underpinned by robust research, are recommendations of (UIL b, p. 88).

Temporal scales matter too. Design decisions made early in life will affect later system capacity and performance, while through–life management will be vital because changes in asset condition could impact services in unexpected ways. How might the later enhancement of one element of infrastructure enable or impinge upon the delivery of services, especially if initial service design assumptions are contravened?

In their exploration of these interactions, UIL (UIL a, p. 25) give the example of the condition of road markings (an asset attribute) affecting the performance of autonomous vehicles (a service that may, in part, depend upon asset condition). It is here that concerns about the capacity of today's data schema and frameworks to manage condition information about decay and deterioration, described in the section on managing legacy assets (B3), may couple across into service performance.

S3 Develop and manage services integrated with and delivered through the built environment to deliver value for users and investors

With desired outcomes understood, benefits discerned and the linkages between contributing systems and drivers all mapped out, attention turns to the capabilities needed for the design, development, prototyping, management and delivery of services. This document focuses on five, beginning with the design and development; then moving onto the creation of the commercial vehicle that structures the creation an reward of value; designing the mechanisms by which data, information and tools will be used to monitor and manage the service; and finally acknowledging the importance of managing the assets to support the services as well as managing assets for value in their own right. There is overlap with many of the issues discussed in VALUE, here with a focus on services. There are also considerations about the data regime, for example in the trade-off between data openness and privacy (see DATA). Similarly, this is cross-referenced other parts of this document throughout.

Because the topic of services is wide, this document presents a narrow selection, looking only at the interface with the built environment in the context of digitalisation. Described below are various capabilities needed to underpin this process:

- Design and create services that exploit the capabilities offered by digitalisation of the built environment and benefit from increasing integration (S3.1)
- Create the business models, commercial relationships and contractual underpinnings to develop, deliver and exploit asset intensive services (S3.2)
- Create the monitoring and management data, information and tools for services and their underpinning built assets, through-life (S3.3)
- Define, monitor and manage asset attributes through-life to enable and enhance services (S3.4)

S3.1 Design and create services that exploit the capabilities offered by digitalisation of the built environment and benefit from increasing integration

Our focus here is on services that are embedded in or delivered through the built environment and the impact of digitalisation on those services. Servitisation of the AECO sectors, although important in changing the dynamic of the sector, is not addressed. The focus here is on the opportunities and impact of digitalisation in this integration. Does digitalisation offer opportunities to tie the service and asset more closely together to develop a better or more robust service? Can we use data from the built asset to better manage the service or to give warning of problems that might degrade the service? In DATA, models of service operations built to interact with models of the asset are proposed. That section goes on to discuss how the integrated models might be used to make better decisions and highlights the need for governance systems and modelling environments that reflect the greater integration of the real service and the real asset.

Conceptually, though, there is great potential in using computer simulations of service operations, coupled to models of the built assets, to better understand the interplay. This is best done by exploring the service process and identifying 'touch points' between the service and the asset; points where data and information from one can be transferred to the other in order to support better decision-making. This data could be real-time, for example, the availability of a built asset resource at the moment of enquiry. Alternatively, the data or information could be historical, for example, showing patterns of past asset performance or of service demand in order to infer lessons to optimise the management of both. Using computer simulations also allows projections into the future to forecast likely outcomes or to create and explore 'what-if' scenarios and questions.

It will also be necessary to consider the characteristics of the asset. Is this a pre-digital legacy asset with limited amounts of data and information available? Would the opportunities created by identifying service-asset interactions justify the addition of sensors of various forms? Then these opportunities can be modelled to understand likely performance and cost. At the other extreme, what are the opportunities to influence the early stages of specification of a new building or infrastructure in order, perhaps, to specify the installation of sensors that can later be used to optimise the management of the services. More ambitiously, service providers can explore opportunities not so much to digitise current practices, but to explore from a blank sheet of paper what options exist to design something completely new (Future Cities Catapult, 2016b).

Developing and using these capabilities will require increased familiarity with computer modelling and with the management processes to make best use of such models for service development, service prototyping and, ultimately, service management.

The Government Digital Service (HM Government, 2019b) is a potentially valuable resource for service designers in the private sector as well as government, covering, for example, end-to-end service design (Gill & Marsh, 2018), measuring performance and success (HM Government, 2019c), and signposting communities of interest (HM Government, 2019a).

UIL present an extensive exploration of the energy and transport sectors to illustrate many of the capabilities that will be needed to exploit digitalisation and integration with the built environment (UIL b, table 6). Generalising from their findings, of particular note are the needs for:

- Evaluation of socio-economic implications of and from infrastructure
- Systems models of the increasing integration
- The capability to define outcomes and the links between services, infrastructure and built assets
- Presentation of information and engagement in decision-making in a more digital world with a wider group of stakeholders
- Exploration of new offerings and the commercial vehicles (including the supply chain) to deliver
- An understanding of the mutual dependencies between services and their enabling assets.

An important part of the specification capability will be the definition of the contribution of data and information and therefore the ability to specify the attributes of the data and information sets and the required quality and performance of the data and information streams (see DATA for further discussion of such attributes). Capturing these requirements will be a key part of the process and content of contracts with adjacent parties. There is also an opportunity here to articulate expectations of other bodies that are not subject to contract, and therefore to identify dependencies and risks.

Specific design and operational demands may need to be made on new assets, on the development and enhancement, and on the refurbishment and repurposing of legacy assets. These then link to the capabilities discussed in BUILT ENVIRONMENT. This, of course, highlights a set of issues familiar to sectors such as railways and explored by their use of integrated asset data management tools and integrated decision-support tools (RAEng & IET, 2019). There are likely to be valuable lessons that can be transferred elsewhere.

None of this is static. As well as the capability to create and develop, be it services, assets or information and data, there needs also to be the capability to measure and monitor performance, to manage accordingly and to manage in the light of the outcomes as a whole, avoiding the risks of local optimisation that undermines system-wide performance (RALW, p. 32). Hence there is an essential link to the ability to understand and forecast the performance of complex integrated systems (G4).

With the service designed in outline, then attention turns to designing the business vehicles that will deliver the integrated package of services and asset outcomes, and to assuring the underlying data and information flows. This is described further in the next sections.

S3.2 Create the business models, commercial relationships and contractual underpinnings to develop, deliver and exploit asset intensive services

This section picks up the third of UIL's recommendations (UIL b, section 4), which was also highlighted in our consultations, that value creation through new commercial relationships and business models for asset intensive services must be established. The capability to do so almost exactly matches the capabilities described in discussions of value (V3), but with specific focus on the issues of service specification, design and delivery with the added complexity of the linkages to built assets and their performance. This capability will be greatly assisted by capabilities in modelling and in the management of integrated data and information about the asset (via a model of the asset), the service and, potentially the business itself. Turner Harris (TH, p. 38) discuss the potential for real-time reporting of utilisation and financial performance. However, UIL (UIL b, section 3.3.1) point out that the business case for such modelling remains to be made. This, then, is both the starting point and the ultimate realisation of this capability.

An example of a new business model in the asset-dependent service space is 'Energy as a Service' where a multiplicity of services might be bundled; insulation provision, more efficient equipment, optimisation of energy supplier and so on, all underpinned by data and information (UIL b, p. 24). This landscape is changing quickly (Innovate UK, 2018) and with it the supply chains, ownership and alliances among the actors. In some cases, sophisticated modelling could be valuable, for example in evaluating the returns on insulation or, more ambitiously, for modelling and exploring 'occupant thermal comfort'. The potential for 'Comfort as a Service' has been explored, as have the implications for thermal management of buildings provided with greater data availability (Buckman et al., 2018; Laing & Kühl, 2018). CAR (CAR p. 91) also highlight the potential for monitoring occupancy data as a way of optimising energy performance and potentially for measuring occupant comfort and response to transient phenomena such as temperature changes, air quality and vibration, though sensor capability is an issue today. They note both that measures such as these might translate into improved performance of occupants – and also that privacy issues will be pivotal.

The vexed issue of investments that are decoupled from benefits arises here. For example, how will costs incurred in building particular attributes of assets be reconciled with decades of benefits derived from the services? How should an asset developer be rewarded for investing in advanced data and information management capabilities when those capabilities will benefit service providers who not only are not party to the contract, but who may create and provide services that are not even envisaged today? This is one area where models are likely to be essential to forecast and underpin trade-offs in costs and returns. This will entail a sound foundation on an asset model, on top of which can be built a model of the appropriate service and on which can be built models of the business and the forecast costs and revenues. In this way, such models can support the design decisions around business models and business management processes.

The creation of business models which extract value from information management, for example in the use of digital data to improve service delivery in healthcare infrastructure, requires a systematic approach and developing this capability is a recommendation of the FOuNTAIN Network. They recommend the creation of a value-driven process model as a route forward (FOuNTAIN, section 6).

By exploring the sensitivities of the modelled costs and revenues to different parameters it becomes possible to identify the most important aspects of the systems of assets and services, and hence it becomes possible to articulate key responsibilities and liabilities to be measured and contracted (UIL a, p. 81). At the heart of business model development lies the matter of risk and reward, explored by UIL (UIL a, section 3.3.5).

Novel business models and evolutions of today's models will be needed to best exploit the linkages between services and assets and to reflect the leverage available from co-investing and co-managing services and assets in a more integrated manner. Business model development is not easy and for practitioners it can be difficult to appreciate the scope of options open to them. Creating taxonomies of business models, especially those that exploit service-asset interactions and creating appropriate guidance in support of exploring new business models would be of great value in enabling this capability. This could usefully be matched with a taxonomy of contractual options and vehicles illustrating options in the space.

Business models that rely on platforms[40] are likely to play a key role in digital built Britain, both because of the potential to act as a link between assets and services (for example as part of the sharing economy, where Uber and Airbnb both create a market between owners and managers of assets and citizens seeking a service) and because of the significance of data and data assets. Data will underpin any platform business models that might be part of access control or of transaction management at the interface between assets and services. WeWork exemplify the revolution promised in the provision of 'Space as a Service' based on their use of data to underpin the offering. These new business models have the potential to disrupt other actors within the industry (Leclercq-Vandelannoitte & Isaac, 2016; Sargent et al., 2018). There is a flourishing literature on the role of business models in servitisation, and there is still much to be done to help organisations in the AECO sectors to embrace this capability.

Uncertainty and risk will play a large part in this debate as the risks associated with assets couple into the risks associated with service provision. Outcome-based contracting becomes more challenging as the dependencies increase. The shift in the military from assets to capabilities

[40] https://en.wikipedia.org/w/index.php?title=Platform_economy&oldid=899015180

continues to be a focus of attention and there is much to be learned by analogy in designing both service architectures (Russell et al., 2008) and business models (Batista et al., 2017).

Service providers will, in many cases, depend upon the condition of the underlying assets. Understanding the interplay (S2) will be important in understanding critical parts of the business model and its sensitivity and such a capability would be valuable (UIL b, section 3.3.4). That interplay will also affect issues of authority, responsibility and liability allocation between contracting parties throughout supply chains and at the service / asset interface (UIL a, section 3.1).

Service providers will also depend upon the provision of data and information about the underlying assets to agreed levels of quality and timeliness. Such data, information and the accompanying measures of data quality will lie at the heart of building and using models of built assets – and also in making the information and insights available to the service managers who depend upon the assets. This will be critically important in complex and integrated systems. Models will play a key part in understanding asset condition and decay mechanisms and the potential impact on services, again exemplified by rail industry research (Kilsby et al.,2017). Computer models will be the foundations to underpin insight and decisions here (UIL a, p. 80).

With the structure, commercial value and liabilities associated with the data and information now being defined, itself a key capability, (UIL a, p. 81) the specifications of required data and information, and of required asset attributes and performance can be enshrined in contracts which define performance, responsibility and liability.

S3.3 Create the monitoring and management data, information and tools for services and their underpinning built assets, through-life

With the service designed and with the business model clear, it becomes possible to assemble the measures and tools by which the service performance and processes can be managed. Much of this links to the organisations' use of data, information and models for management (DATA). Process maps will be a valuable tool for this, and the DFTG Roadmap[41] calls for creation of industry reference process maps to highlight where decisions are made and hence dictate the content and quality of the enabling data and information. Such reference processes may be useful, both to stimulate innovation and as a benchmark for service designers and managers.

As well as raw data and information there is much to be gained by decision-support tools. These begin with the models, increasingly federated, for example the simulations of complex integrated systems (G4) and progress to the use of digital twins (SW – Systems). Development of digital twins can model not just the assets, but also the services that depend upon assets. This will depend upon the ability to articulate and quantify the linkages between them (S2). Explicit modelling of data and information, both their provision and quality will further help the capability.

[41] Task 3.2 in the DFTG roadmap (Enzer et al., 2019).

Early use of models will help scope designs and explain interactions; predictions of performance will assist in the specification of assets, data and services. Use of models through-life can underpin operational management decisions, now with a better understanding of cause and effect. Common practice within operations management in the manufacturing and process industries, extending from start-up simulations to maintain safety though transient conditions all the way to training simulators, there may be lessons to be learned. There is research into simulation associated with the construction phase and facilities management, for example in the USA (Behzadan, Menassa, & Pradhan, 2015), setting out future directions and exploring performance indicators. Opportunities exist to use simulations as a tool to create key performance indicators that glue together the interests and systems of the service providers and the underlying asset and facility managers (Lavy et al., 2014). However, outside of those domains in which there is a total dependency of the service upon the asset, such as rail and road, there is little work linking facilities management and the management of built assets explicitly to the task of underpinning the performance of embedded services. How can the management of built assets enhance services such as education and commerce? A notable exception to this is the health services sector, for which there is a small body of literature exploring the effect of hospital design on patient outcomes and experience (e.g. Patterson et al., 2019) and the work of the Health and Care Infrastructure Research and Innovation Centre[42].

A foundation of this capability will be the shared data and the robustness of a 'single source of truth' provided by models, including historical data, 'as-is' models and predictive models. The current philosophy of the Common Data Environment is a good practice starting point from which the industry can build (UIL a, p. 58). This too can inform the supply chain/ecosystem process models, and links closely to the capabilities in specification of data and information quality (D4.2).

S3.4 Define, monitor and manage asset attributes through-life to enable and enhance services

Increasingly, we will need to create and manage built assets specifically in support of defined services. This is common practice in industries such as rail (Kirwan & Gradinariu, 2010), road[43] and energy, where it is already subject to the changes wrought by digitalisation (Shetty, 2015), but this thinking will be further extended throughout digital built Britain, even for domains in which there is less dependency of the service upon the asset. Exploring this interplay was the valuable contribution of the Health and Care Infrastructure Research and Innovation Centre[44].

Asset condition has the potential to profoundly influence the performance (and even safety) of the services delivered in the built environment. UIL point out, for example, that deterioration in road makings could impair the operation of autonomous vehicles (UIL b, p. 16). In another example of

[42] http://www.haciric.org/
[43] http://www.highwaysefficiency.org.uk/efficiency-resources/asset-management/highway-infrastructure-asset-management-guidance.html
[44] http://www.haciric.org/

the tightly coupled interplay, specific research (Prorok, 2018) is currently supported by CDBB to explore the co-evolution of the built environment and mobility solutions. Other examples abound in the railway industry, where service performance depends so profoundly on asset condition.

CAR's report for CDBB focused in particular on the use of digital tools in the management of legacy assets, and especially the creation and maintenance of accurate and digitally supported representation of the 'as-is' condition (CAR, p. 56). This is discussed further in section B3.

Specific attention must be given to the likely performance and management of services in the face of assets that are damaged or disrupted. This was highlighted in early CDBB workshops (SW – Stakeholders and SW – Systems) and is a further development of the vulnerability and resilience (G4) debate.

As the UK increasingly integrates services with the built environment, and as such integration increasingly comes to depend upon flows of data, information, models and other tools of digitalisation, so the capabilities discussed here become increasingly critical. Certainly, defining outcomes and value from services, understanding the interplay between services and assets, and finding ways to fund developments will be pivotal. Research can and should contribute to each of these.

BUILT ENVIRONMENT: Develop and improve the Built Environment across its lifecycle, embracing digitalisation

The introduction below provides an overview of the **Built environment** category of the Capability Framework for creating a digital built Britain.

Click here for an introduction to the **Capability Framework** as a whole, including links to all the categories involved.

Built environment capabilities

Enable our buildings and infrastructure to embrace digitalisation across the lifecycle

- Evaluate, manage and protect the natural environment alongside the built environment (B1)
- Model and manage interactions between built assets, infrastructure and services (B2)
- Use data, information and models to create and manage assets for value through-life (B3)
- Develop and adopt new digital technologies and tools (B4)

Introduction

The data generated by a digital built Britain will enable more cost-effective creation and management of our built environment throughout its lifecycle.

However, we also need to consider how digitalisation will help us to manage the impact of our buildings on the natural environment. Even in the densest of built environments, we rely on ecosystem services for resources, water management, beauty, health, emotional wellbeing and other contributions. As our demands from the built environment grow, our actions to protect the natural environment must also increase. Can we use computer models to help us make better decisions and manage the built environment in ways that will avert climate catastrophes in the future?

We will live in a world of increasing integration – between services and assets, between different kinds of infrastructure and between growing numbers of organisations in complex supply chains. Decisions made when managing assets or infrastructure will inevitably affect any dependent services, and vice versa. Understanding the implications of these complex integrations is essential if we are to avoid unforeseen consequences. What capabilities will we need to manage these interactions and the huge amount of underpinning data?

We aim to digitise the entire lifecycle of our built assets, finding innovative ways of delivering more capacity from schools, hospitals, roads and rail networks. What new capabilities will we need to collect and use the huge amount of data this will generate more effectively?

For example, we need to work out how to collect data from pre-digital assets that have not been enabled by such technologies as Building Information Modelling. For assets that are already digitally enabled, owners and managers need the capabilities to optimise the use of the data throughout the building's lifespan. What kind of value can we gain from a building's historical data sets that could become a tradeable asset and be worth nurturing?

New digital technologies, together with growing levels of data and information, will support new ways of working, providing the potential for increased levels of efficiency and effectiveness. However, adopting and assimilating new technologies carries risks. What capabilities do we need to access the benefits while managing the risks and uncertainties?

B1 Evaluate, manage and protect the natural environment as an essential resource for and partner with the built environment

The natural environment is a context for and driver of life in digital built Britain, and a source of many important benefits in its own right. Therefore, protecting it and managing it must be a key capability, identified in the CDBB consultation workshops (SW – Context). Of particular interest here is the development, improvement and though-life management of built assets and infrastructure to that end. In particular, we must understand how digitalisation will change the interactions between the built environment and the natural environment, whether such changes will be for better or worse, and how to use data and information and digital tools to mindfully manage such interactions and changes for the benefit of current and future citizens of digital built Britain.

The underlying capabilities behind this are to:

- Translate into specifications, targets and constraints the ways in which the built environment is to be managed with respect to the natural environment (B1.1)
- Enhance system modelling perspectives to broaden consideration of natural environment issues (B1.2)
- Design and use metrics for managing the interactions between the built and natural environment (B1.3)

B1.1 Translate into specifications, targets and constraints the ways in which the built environment is to be managed with respect to the natural environment

Building up an appreciation and understanding of the value and interaction with the natural environment is a fundamental starting point. From here, we must develop the capability to translate into specifications, targets and constraints the ways in which the built environment is to be designed, developed and managed though-life in order to best manage the built and natural environments and their interplay. This translation is essential in order i) to make visible the requisite actions and priorities, ii) to enshrine them in demands made of service providers and asset owners and managers, and iii) to embed the considerations within business models and supporting contracts.

Essential to this process is an explicit unpacking of what value the natural environment represents and, as explored in the VALUE section of this framework, the answers are likely to be diverse and complex. The Valuing Nature Network[45] is a multidisciplinary research network exploring issues of how the natural environment provides value and is valuable in its own right. Once we have negotiated an understanding in this area we can begin to weigh the value of the built environment against it. How can we capture the value of biodiversity to future generations who may experience ecosystem collapse in their food supply? How do we balance the beauty of a forest against the usefulness of a housing development? How can we ensure that planners and policymakers factor these forms of value into decisions that will affect the natural environment?

Better data, information and tools will have a part to play and they will be better used if designed to support insights and decisions about interactions between the natural and built environments. It is important that the UK build the capabilities to ensure that the data sets and models used for the natural environment can be interoperably interfaced with those used for built assets. Data, model, process and governance must be aligned between those used for the natural environment and those used for the built environment. There will also be a matter of scale and must encompass all the issues of linking GIS systems with the other forms of data and models.

B1.2 Enhance system modelling perspectives to broaden consideration of natural environment issues

The relationship between the built and natural environment goes beyond efficiency and damage limitation, as encapsulated above. Built assets and public spaces coexisting with the complex natural systems of the changing planet requires a new approach. 'In terms of the regenerative built environment, this approach will require a shift away from the narrow focus on building energy performance, mitigation strategies, and minimisation of environmental impacts to a broader framework that enriches places and their inhabitants, ecology, and culture, and makes cities resilient to climate change and changing human needs.' (Naboni et al., 2019)

To underpin the understanding of these issues and interactions we will need the capability to build and enhance our tools, especially in the modelling of the complex systems (G4) at work. Hence, the system modelling perspectives must continue to build on and to broaden the current consideration of natural environment issues. Just one example of current work is the MISTRAL (Multi-scale Infrastructure Systems Analytics) modelling initiative (Hall, 2016a). Another example lies in the modelling of environmental dynamics, such as flooding, in the context of built assets such as flood defences (Harvey, Hall, & Manning, 2014). Pursuing such initiatives and conducting such work will further develop and use of such tools to enhance understanding, inform policy and design and

[45] http://valuing-nature.net/

enable better-through life management of assets at the interface of the built and natural environments.

As well as the tools, there is work to be done in the better creation, management and sharing of data across the scales that apply to the natural environment and to built assets, ensuring that data sets from large scale, such as GIS, can be appropriately linked to other scales. With the breadth of disciplines involved it will be important to carefully manage the matters of language and of mental models, of labelling, curating and sharing data (RALW, p. 42). Hence, there are links between this capability and those discussed in DATA. There needs also to be an interface to work planned for Tasks 1.1, 1.4, 3.1, 3.3, 3.4, 3.5, and 3.12 plus the 'Enablers' and 'Change' themes on the DFTG Roadmap (Enzer et al., 2019).

It is vitally important that the system perspectives and tools that encompass the natural environment mesh seamlessly with their counterparts so that systemic modelling can best represent the reality of the interplay between the built and the natural environment.

B1.3 Design and use metrics for managing the interactions between the built and natural environments

Arising from the deeper understanding of the interplay, from the formal specification of outcomes sought and from the better system modelling tools lies the potential to create a further capability – that of designing and using metrics for managing the interactions between the built and natural environments. With these metrics in place, there will be the basis for coherent management across interfaces; a management that recognises and respects the significance of the natural environment in digital built Britain. These, then, are the tools and frameworks through which we can change the relationship between the built and natural environment from one of exploitation to one of greater balance. The high priority of this work has been set by the Government through its target of net zero greenhouse gas emissions by 2050 (Harrabin, 2019) and its designation of climate change as an emergency in May 2019 (Walker, 2019).

B2 Model and manage interactions in coupled assets, infrastructure and associated services

It is important that policymakers, decision-makers, owners, developers and managers are alert to the interaction effects that will emerge as assets, services, organisations and data and information become ever-more tightly integrated. Only by being aware of these interactions and the ways in which the integrated systems are likely to behave can the public, owners, managers and providers forecast the effects of their actions and decisions, choose the best and manage their part of the system through-life. The capabilities discussed here will depend upon the modelling and the underlying data and information (DATA).

Such modelling can explore not just the assets, services and data in question but also the coupling of these. Such coupling might arise in many ways:

- From asset performance, especially as it changes over time, either due to deterioration, change and upgrade or refurbishment. UIL note, for example, that deterioration in road markings could impact the performance of autonomous vehicles (UIL a, p. 25). It is easy to conceive of other instances, for example where transport assets interact with power and communication assets, where the design of transport nodes affects the performance of all the transport sub-systems
- From service performance, especially where the services are key to maintaining and managing the assets, or where the assets enable the services. For example, what happens and how does one manage a digitalised asset in the face of a failure in a 'Software as a Service' function? What are the implications of a breach in security?
- From interactions between organisations, say between the government departments and agencies responsible for procuring, funding and managing infrastructure assets. Service providers and asset developers and owners depend upon their supply chain ecosystem and so therefore the performance of the whole might depend upon the performance of a minor part of a larger programme (Aritua, Smith, & Bower, 2011).
- From data-based interactions which may not be as dramatic as the consequences of data failures, but may be more insidious, such as the impact of data biases or missing data (see (Ruffle et al., 2014) for an example). The data interactions (including communications channel performance) may lead to increased fragility and vulnerability of integrated assets as well as the benefits offered by ubiquitous shared data.
- From the emergent effects of loosely coupled systems, explored in the domain of 'systems of systems' (Cavalcante et al., 2017; Urban Foresight, 2018; Nielsen et al., 2015).
- From exogenous drivers and contextual events (CONTEXT).

By creating and exercising models of the built environment reflecting such interactions, stakeholders can explore future decisions and initiative to check performance expectations, to understand emergent properties such as security, vulnerability and resilience, and can do so while considering the whole life of built assets, infrastructure and the associated services and data. Just one example of this thinking is the new insights about the circular economy and a supporting research framework from (Pomponi & Moncaster, 2017), which give due emphasis to through-life thinking.

Many argue for the merits of an agreed and authoritative source of truth about an asset. It is already recognised that a key interaction which needs improvement is in the handing over of data between the construction and operational phases of the built asset and the different organisations associated with each. Indeed, Turner Harris see the transition from 'handover' to 'seamless persistence of validated asset information' as one of the big opportunities (TH, p. 7).

Current barriers include limited understanding of what data and information should be exchanged, as well as lack of awareness of the value it can generate (CAR, p. 17 and p. 23). Companies working across the service / asset gap need to build a shared understanding of the value and attributes of the data that they can and should share. Hence the pursuit of a single reference source of data provides a way to i) clarify any interactions that will arise from sharing data, ii) minimise the chances of 'invisible' interactions from differences in understanding about asset status and its impact on services.

Representing and communicating uncertainty is a critical capability in managing interactions and interfaces, especially between collaborating organisations or organisations that create data for others' later use. CAR identify this as an important capability that deserves attention (CAR, p. 23).

B3 Use data, information and models to better manage assets for value through-life

This section unpacks the component capabilities that underpin the creation of value from assets. It does not revisit the questions of discerning value (V1), or of the interaction with services (S2), as those can be found elsewhere, but instead focuses on the built environment and its management.

It begins by identifying the importance of clarifying objectives and expectations around matters such as optimisation versus satisficing. It goes on to consider the implications of using data and digital tools and the need for more sophisticated organisational processes and governance. The details of supporting capabilities are discussed elsewhere, in DATA. Then it turns to the capability to manage the assets, focusing only on the implications of digitalisation. Conventional asset management capabilities are not explored here. Finally, it describes the capability to manage the data and information as valuable assets in their own right.

The underpinning capabilities are to:

- Choose management strategies that enable pragmatic management of potentially complex sets of assets (B3.1)
- Acquire and integrate data, information and models as tools for the management of value (B3.2)
- Use digital tools, data and information to better manage built assets through-life (B3.3)
- Manage the value of the data assets created from working with the built environment (B3.4)

B3.1 Choose management strategies that enable pragmatic management of potentially complex sets of assets

One trap to beware as data becomes more available, as models are developed and ambition rises is the chimera of optimisation. True optimisation depends upon being able to accurately define the relative mix of probably conflicting objectives (the objective function); this despite the difficulties of articulating the value and priority of intangible outcomes (V1). Furthermore, one needs to know whether and where within the operating envelope might lie the dangers of local optima that are less than global optima, but are more easily attainable, a concept known as the fitness landscape). Finally, in a real world of non-linearities and feedback loops, the task of calculating and then achieving pragmatic solutions to optimisation is difficult. Hence, as highlighted CDBB consultation

(RALW, p. 39), it is important that policymakers and decision-makers decide between optimising and satisficing strategies in management practice.

B3.2 Acquire and integrate data, information and models as tools for the management of value

The focus here is on the capabilities needed to assemble and adopt into everyday use an appropriate portfolio of tools to manage benefits and costs from built assets. However, deciding which data and information are needed, choosing the right tools for the job in context and then integrating these tools into suitably modified work processes is a major undertaking and a capability, and one which is not well distributed across the sector. Driven by increasing integration of tools and data down the supply chain, these capabilities are needed also by SMEs and that the performance of the entire supply chain may depend upon the digital competence of others, further complicating the process.

Other industries have adopted digitalisation enthusiastically, giving rise to the term Industry 4.0 to refer to the boom in digitally enhanced manufacturing, supply chains and product lifecycle management practices. However, there are undoubtedly characteristics of the construction industry which will impede adoptions. A survey of Industry 4.0 concepts and their potential adoption (Oesterreich & Teuteberg, 2016) identifies three promising clusters of opportunity; the smart factory, simulation and modelling, and digitisation and virtualisation. They go on to identify barriers and benefits which closely match those found through CDBB consultation.

Adoption of tools

Adopting new digital tools is found to be difficult, with CAR identifying barriers to the adoption of tools in general (CAR, figure 4-2) and (Vision, p. 8 and p. 21) exploring the barriers to the adoption of immersive reality tools. Both found that concerns about the new technologies revolve around standards, a stable market and interoperability. The Vision Network notes, from its research questionnaire, a social factor in the aversion to the adoption of new technologies. Skills shortages and the costs of training appear as concerns raised by many commentators. Any need to hire new specialists constitutes a major barrier to adoption.

CAR created an overview from their interviews of the current use of digital tools, mapped against their proposed key capabilities. This diagram (Figure 2) shows the prevalence of tool adoption in the early stages of the asset lifecycle and, by implication, the potential remaining were such tools adopted and applied in other parts of the asset lifecycle.

Supporting this observation of the current focus on early stage value, and recognising the later opportunities, Turner Harris identified sixteen use cases where digital tools have the potential to add value (TH, p. 8). Most cases seek and expect value from the through-life continuity and communication of information and insight.

Finding routes to adoption of their technology that are lower cost or lower risk is a recommendation for developers that is explored further in the section on developing new technologies (B4).

Figure 2 - Map of current digital technology use (CAR)

Adapting processes to make best use of tools

Inevitably, companies will need a portfolio of tools and to find ways of making them work together. CAR (CAR, p. 21) quote Chen et al. (2015) regarding a lack of studies in this area while Ilter & Ergen (2015) note only a few early studies of BIM in refurbishment processes, so it is likely that finding ways to integrate BIM, FM systems, data acquisition and management tools is an area of weakness. The topic was also raised in the CDBB consultation workshops (SW – Systems).

The section on data, information and models (DATA) discusses the utility of models and simulations as tools. This section, in contrast, discusses capabilities associated with managing such tools to develop deeper insights and to make better decisions.

- Deciding what models to build and how to use them.

  Models can vary considerably in sophistication. At its simplest, the representation might simply include data and information about the current state of the asset. Historical information provides a resource that can be interrogated to understand the implications of past actions, events and changes. However, with predictive computer models, owners and managers can forecast the future and explore options before taking decisions. This, however, assumes an organisational context able to make use of such tools.

Furthermore, as the models are federated together into interoperable combinations, so the performance of clusters or systems of assets can be reviewed, forecast and managed. The organisational context becomes more complex, for example, spanning several organisational entities.

- Designing the organisational contexts within which models can be used to best effect, encompassing for example management processes, metrics and performance indicators, organisational governance systems.

  Organisations today are used to the systems and governance policies within which they use BIM models. The extension towards the use of dynamic models will have the same elements; however, the greater power of such models deserves attention. As models come to reflect the greater integration of services with assets, so the management process design must reflect this. More cross-linking implies more complex management processes. The mapping of processes to show the decisions to be made and hence the implications of, and need for supporting data, is recognised as an essential task (3.2) within the DFTG roadmap (Enzer et al., 2019).

  Models will also lie at the heart of the processes of demonstrating and confirming compliance with prevailing regulation and guidance, used by many parties throughout the asset's lifecycle (D-COM, figures 7 and 8).

  As models are used for service operations management and for key business decisions, so security and decision-rights must be revisited. The models will become increasingly valuable in their own right, especially as sources of competitive information. The organisational context and the sophistication of models being used must co-evolve (Wan, Nochta, & Schooling, 2019). Finally, governments and companies will need to develop their professionals' skills (L2) in the use of these tools and their supporting processes.

- Designing the organisational contexts that enable integration of models into larger systems – likely to be between different organisations, and hence touch upon management processes, metrics and performance indicators, organisational governance systems.

  If the modelling of built assets is to develop across all scales and for complex systems then there will need to be equivalent understanding and, potentially, interfaces for the organisations involved. These could include component and subsystem suppliers, for example HVAC plant into a building, all the way up to interacting large corporates, for example building owners and city authorities. Governance across these organisational boundaries becomes ever more challenging as scale increases, especially as the context becomes more complex (Nochta, 2019). Organisations may find themselves working in strategic partnerships with IT and data specialists, as has happened in the defence logistics sector (Lamb, 2018b).

There are several calls for the development of common platforms that, together with standards for data and information content and quality, will enable multiple organisations to co-operate (TH, pp. 9, 18-19; CAR, pp. 8, 39). Importantly, such platforms also create the confidence to invest, by building greater assurance that valuable data and information resources can be shared, traded and otherwise used with a minimum of barriers and blocks. However, beware any technology-dependency in such platforms, because one of the primary barriers to adopting new technologies within the industry is fear of technology change that leaves investments wasted (CAR, section 3.3.3).

Such platforms will also have a profound impact on the entire supply chain, including SMEs that are at some remove from the ultimate client.

Digital twins entail linking the model to the real asset in real time and using comparisons to build insight, to forecast and to make management decisions (Bolton et al., 2018). Organisations will need to explicitly decide their objectives before they can choose their digital twins, for example using a classification such as[46]:

- **Component twin**: to manage topics such as failures / replacement / performance.
- **Asset twin**: to manage topics such as maintenance / performance / availability / operation.
- **System twin**: to manage topics such as service reliability / Overall Equipment Effectiveness / investment / organisational performance.
- **City twin**: to manage topics such as public services performance measurement / mobility / emissions.
- **National twin**: to manage topics such as health / education / security / resilience.

Capabilities to develop and use digitalisation, along with appropriate management processes in pursuit of hazard and safety management offer massive benefits, albeit hard to measure if successful. Turner Harris identify capabilities associated with hazard monitoring and management, pointing out that the convergence of sensors, of computing power, analytics and organisational processes offers big wins, albeit with development needs, especially for applications in legacy assets (TH, p. 40).

B3.3 Use digital tools, data and information to better manage built assets through-life

Data, information and models (see DATA) will be central to the management of built assets within digital built Britain. The focus here is on the capabilities needed to best make use of the information and models to create insight and support decisions about the assets.

A survey conducted of BIM research in 2016[47] showed that there is still a predominant focus on the design phase, suggesting there is still potential for further research into the use of tools such as BIM and its derivatives in later lifecycle phases.

Perhaps the most significant element is not so much the development of a capability as the development of a philosophy of 'the persistence of data' rather than 'the handover of data'. This is central to the recommendation by Turner Harris of 'seamless persistence of validated asset information' as a key capability for digital built Britain (TH, p. 34). Although there is a current focus on data and tools in the early stages, there remains much to be done to use tools and data to extract value through-life (TH, p. 4).

[46] Parlikad, A., Private communication, 13 February, 2019.
[47] https://www.bimthinkspace.com/2016/09/global-trends-in-bim-research.html

The handover transition is one of the greatest missed opportunities for value management in the lifecycle of built assets today. Turner Harris (TH, p. 7) highlights this as one of their key messages as, independently, do CAR (CAR, pp. 23, 93). Because today, 'Data and Collaboration platforms are predicated on 'handover' rather than persistence',[48] data and information fails to be managed across the transition, together with the opportunity to build a lifetime of asset history on a stable foundation. Early work here clarified that there is value well beyond the safety and regulation imperatives, addressable by earlier involvement of facility management teams, integrated tools and standardisation (Whyte, Lindkvist, & Hassan-Ibrahim, 2010).

Working with legacy assets requires yet more effort. Despite all the enthusiasm for digital technologies associated with design and build, the operate phase and working with legacy assets will be a vital aspect of digital built Britain. After all, over 80% of buildings already built are likely to still be in use by 2050 (CAR, p. 9), and most of these have no digital data or information associated with them, either current or of their history. Therefore, a key set of capabilities, identified by CAR, are those around capturing a picture of the current reality of the as-built asset (CAR, section 4.3.1). Until a building has an associated body of digital data gathered, processed and available then it cannot be managed 'digitally'. Hence the importance of enhancing the UK's ability to build good data sets about legacy assets and then manage such data sets.

The accompanying imperative is to make this task practically and commercially feasible, entailing automation of gathering and managing such data (CAR, section 4.3.1)[49]. The cost, skills demand, complexity and the need for high levels of human intervention in such a process today undermines the whole investment case today for digitisation of legacy assets and so each of these aspects constitute a target for research and development.

The data management includes the underlying processes of data exchange and translation of survey data into information, for example of point-cloud data and its integration into BIM and GIS data sets (CAR, pp. 17-18; Rashidi & Brilakis, 2016). Other pragmatic issues are associated with surveying 'hidden' services (pipes, wires, and plumbing) embedded within the asset. CAR note that this is an issue raised by practitioners during their interviews, but is almost entirely absent from the literature (CAR, p. 19). The other part of this required capability is the linking of semantic information of attributes of the asset, so capturing the fine detail that adds so much extra value.

There is considerable potential in looking beyond just 'data' to a more diverse range of information. According to Historic England (2017), BIM can be used to attach a range of files, from digitized archival records and audio recordings of oral history interviews, to condition surveys, inspection logs and other types of material. This can be kept with point cloud data about historic buildings and feed into decision-making, discoverability and engagement with historic buildings. However, there are no existing standards for using BIM for to meet the specific needs of historic buildings, as opposed to legacy assets that are newer, but simply pre-digital.

Data and information about our current building and infrastructure stock is also crucial for building performance and safety. Where there is failure to capture and manage information to an agreed

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[48] Identified as one of the primary barriers to digitalisation in the sector (TH, p. 16).
[49] See also Turner Harris (TH, p. 28) for a detailed exploration of this capability.

framework, crucial and potentially life-saving knowledge can fall through the cracks (Hackitt, 2018a). This means digitising legacy documentation and protecting vulnerable born-digital information, and making them discoverable and accessible according to standards and governance (D2, D4).

Facility management and the use of BIM is a current and developing domain. Ilter & Ergen (2015) proposed research agenda throws up elements of capability that are still to be enhanced. Other early work has shown that BIM and Computerised Maintenance Management Systems (CMMS) can be integrated at the database level, allowing bi-directional transfer of data, and making BIM data useful to the maintenance function (Liu & Issa, 2012).

The second monitoring opportunity is with respect to the performance of the occupants, and the extent to which the asset supports their performance (*ibid*., p. 6). CAR's work suggests there is considerable value to be extracted here, but they note the risks associated with privacy (*ibid*., p. 26) and that current technologies do not produce reliable data. Early work for CDBB flags up the importance of monitoring transient phenomena and the implications, therefore of the sensor fit required (Navarro et al., 2018). While monitoring occupant behaviours and perception holds great promise in allowing feedback and modification to the asset to help the occupants, it will be essential to address the organisational issues in working across the different parties involved and managing privacy (Jalia, Bakker, & Ramage, 2018).

Looking further to the future and more ambitiously, Turner Harris propose the development of the ability to develop autonomous operations and maintenance, enabling Building Management Systems (BMS) to integrate with the digital twin and robotic systems to automate Operations and Maintenance regimes (TH, p. 30). The primary drivers will lie in high hazard environments and in hazardous tasks. Although the most sophisticated systems can be envisaged within say, the nuclear and offshore domains, early instances could be expected sooner, for example with automated window cleaning and pipe inspections systems. Although there may be special cases where such capability is justified on its own, for example when autonomous maintenance can be run during operations so minimising downtime, the big wins will be realised when such capability operates in and contributes to data-rich modelling and management of integrated assets.

As refurbishment, repurposing, or recycling are envisaged, today it is clear that inconsistencies in terminology and taxonomies (Ilter & Ergen, 2015), together with limitations in current software, need addressing before they can fully support these phases (CAR, p. 22). For example, schema and data structures need to be extended to include more nuanced information, including details of decay or the constituent data and information to conduct robust lifecycle analyses. Semantic technologies hold out promise for this and are reviewed for the AECO industries (Pauwels, Zhang, & Lee, 2017) and links between BIM and FM via semantic technologies are trialled by Kim et al (2018).

In all of the above, the dominant issue is that of developing capabilities in data sharing between organisations and across the asset's life (CAR, p. 20). This is not only a technical issue, but also due to a lack of understanding about what information should be transferred[50], for example to facility management teams, coupled with the appointment of facility management teams too late in the

[50] Highlighted as the greatest current barriers by Ilter & Ergen (2015).

buildings life to advise on through-life needs or to fully assimilate the available information (*ibid*., p. 22). Re-tendering of facility management contracts provides another opportunity for data and, especially information and insights from experience to be lost forever.

There exists a portfolio issue across the whole lifecycle for companies that seek to transfer of legacy assets currently in operation, into a digitally managed context, and trying to manage both digitally-enabled and non-digitally-enabled legacy assets under the same organisational umbrella (TH, p. 5). With the complexity and pools of data held in paper-based systems the temptation is to run parallel systems of work for new assets using digital platforms and to sidestep the investment and risk in transfer of legacy data and information. As well as foregoing the benefits discussed elsewhere, there are knock-on organisational consequences of silos of expertise, of curtailed sharing of knowledge and of losing knowledge as staff retire. Investments in upskilling and in knowledge management then become key concerns for organisations with portfolios of new and legacy assets.

The implications of managing fleets or portfolios of assets are explored by Petchrompo & Parlikad (2019), who suggest a classification system for such instances and identify trends and research directions. Although their research is in an adjacent domain, much of the thinking is transferable.

This is but one example of a wide range of issues that need to be considered as companies use ‘hybrid practices’ *en route* to adopting new and digital technologies. The social context and management practice within and between organisations deserve specific attention to understand and then develop management and process capabilities (Harty & Whyte, 2019).

An area of considerable potential which spans the entire lifecycle is to use digital tools to enhance compliance checking with relevant legislation, regulations and guidance (see G1.2). This topic, flagged up at consultation workshops (SW – Systems), was studied extensively by the D-COM Network and their recommendations can be found in (D-COM). In this they lay out a roadmap of steps to significantly build capability.

B3.4 Manage the value of the data assets created from working with the built environment

As well as the value embodied in the built assets themselves, owners and managers will need to build the capability to manage the data, information and models as assets, to curate them, maintain them and ensure continuity and provenance through the lifecycle of the data (see also DATA). The opportunities are not well understood today (UIL b, p. 62). For example, the data and information which shows how the asset was built (as distinct from as it was designed) is of immense value to those tasked with maintaining it. CAR devote several pages of their report to outlining the capabilities needed here (CAR, p. 22):

- Data storage and data exchange – ensuring interoperability
- Transfer of information from construction stage to operation stage
- Capturing and communicating uncertainty
- Sharing data across the industry
- Management of building stock data

- Keeping an up to date model and creating a single source of truth

Similarly, it is the detailed information about construction materials, their provenance and history which lends added value at the end of life.

The data surrounding the use of an asset of service may also have immense value. For example, 'The release of open data by TfL is generating annual economic benefits and savings of up to £130m for travellers, London and TfL itself' (Deloitte, 2017a). Accessing such value will depend upon the business models of the entities involved, but the integration of services and assets will increase the value of data associated with both.

Some data and information are valuable because they are not widely shared or only subject to robust management of ownership and access. Hence an important capability[51] for governments and companies working in this area is the management of the security of data and the management of intellectual property rights (D1.4).

Turner Harris (TH, p. 21) note that the security issue is complicated by the long supply chains which usually include SMEs, raising concerns about fragility and weaknesses due to less cyber awareness among such firms. As discussed earlier, data and information in supply chains is only as secure and reliable as the least digitally literate in the chain. Furthermore, the extended network of companies linked through data systems not only increases vulnerability, but it also increases the breadth of impact from a successful attack.

B4 Develop and use new technologies which are greatly enhanced by digital tools and enabling data

With the amount of research and technology development under way and the pool of available capacity, combined with the uptake of potentially useful technologies in adjacent industries, there is a real need for organisations in the AECO sectors to build the capabilities to adopt and use technologies. This 'demand-side capability' is covered within section B.3.3.

There is an equivalent 'supply-side capability' in the development and provision of technology, and so the focus here is only on technologies for which digitalisation intersects with the needs of the sector. This document comments only on a few indicative technologies.

As evidenced in section B3.3, users face two major challenges that technology promoters must address. The first is to find ways of making technology capabilities accessible without major investment barriers – to find ways of phasing expenditure, ways of trialling exposure, ways of 'toe-dipping before taking the plunge'. This has been adopted as an entire theme by the Digital Manufacturing on a Shoestring team at the Institute for Manufacturing[52], which explores ways of making technology more accessible to SMEs. Addressing this challenge is essential in other areas,

[51] Both topics emphasised in consultation (RALW, pages 24, 32, 36, 41 and 43)
[52] https://www.ifm.eng.cam.ac.uk/research/dial/research-projects/digital-manufacturing-on-a-shoestring/

for example in Off-Site Manufacture (OSM) where initial investment costs are a major barrier (Housing 2, p. 11). Although often expressed as a performance/price trade-off, for industries where there is a long tail of SMEs with constrained resources, the initial cost becomes a barrier irrespective of the performance opportunities on offer.

OSM highlights capabilities that are needed to adopt and exploit that technology, but which also have lessons for others. For broad technologies, or those where the label covers many different aspects it is important to develop a clear vocabulary and definition of terms in order to manage debate and expectations (Housing, section 6.1). Otherwise, people hear unrealistic promises, talk at cross-purposes and often the hype surrounding the technology inhibits its likelihood of adoption, especially within a conservative industry.

The OSM experience also teaches the need for technology promoters to have a deep understanding of the industry practices and processes in order to clarify and characterise the constraining barriers and bottlenecks that block uptake (Housing, section 6.8). Companies fully recognise the additional costs, such a familiarisation and training (CAR, pp. 28, 41), and rightly add these to the investment consideration. Hence, technology developers need to address all the cost drivers, not just the core technology.

There may also be softer barriers to the uptake of a technology, for example social barriers of perception and expectation. The reputation of pre-fabricated buildings is an example of such a barrier in the case of OSM (Housing, section 6.7). Promoters will need to identify and address these barriers to the adoption of a new technology.

Another technology which has received considerable attention across the sector is that of immersive technologies (Whyte & Nikolić, 2018), and this was specifically explored by the Vision Network (Vision). They identify barriers to the adoption of this technology and these can be generalised as capabilities that may be valuable for technology developers and champions:

- Address economic barriers of initial cost, exploring low-cost entry routes or different business models
- Address costs of training and familiarisation, especially if digitalisation can support user interfaces that will support both the inexperienced and the experienced user
- Address concerns around safety and security and misuse, be it accidental or malicious, of the technology, especially important as technology capabilities move into domains which will be new for traditional users.
- Address social and cultural barriers, especially the absence of digital skills and concerns about change management and new ways of working. Recognise that the enthusiastic support of early adopters may be essential (but beware vague generalities that are unconvincing)
- Address concerns about users' knowledge of the market – often users will be waiting for a market to stabilise, while in other cases users will not understand the market or the speed with which it is developing
- Address users' concerns about the direction of technology evolution, especially of standardisation and concerns about technology lock-in (using the Betamax analogy)
- Emphasise the quick wins as well as the long-term benefits

- Endeavour to build end client ‘pull’ for the new technologies, because this has a profound effect on enthusiasm for adoption (CAR, p. 28).

Technology stacks (the set of enabling technologies that underpin a new product) will have a large role to play in the development and introduction of new technologies into the industry. For example, the Internet of Things is, in essence, a battleground of competing technology stacks, as is low power and wide area wireless networks (IHS Markit, 2018). The integration of BIM and data streams from devices from Internet of Things offers interesting options to be explored (Tang et al., 2019). The outturn of these competitions for technologies, for platforms and for *de facto* standards will shape the industry. As wave after wave of technology sweeps across digital built Britain, with candidates including Big Data (Bilal et al., 2016), Artificial Intelligence / Machine Learning (RALW, p. 40) and semantic web technologies (Pauwels et al., 2017) each will need to be supported by these capabilities and the lessons learned from their predecessors in order to succeed.

While promising technologies abound, ready to be exploited by the AECO sectors in designing, building and operating assets in the built environment, often financial, procedural and human barriers prove more difficult to overcome than those of integrating new technology. Particularly where SMEs and legacy assets are concerned, the barriers to technology adoption are high. However, digitalisation of the built environment holds promise – if not of perfect optimisation than at least of better balancing the needs of stakeholders, businesses and the natural environment, through-life.

DATA: Use data, information and models to support better decision-making

The introduction below provides an overview of the **Data, information and models** category of the Capability Framework for creating a digital built Britain.

Click here for an introduction to the **Capability Framework** as a whole, including links to all the categories involved.

Data, information and models capabilities

Use data, information and models to support better decision-making

- Embed models and data as tools in understanding and decision-making (D1)
- Develop and manage data structures, schemas and tools (D2)
- Develop and manage federated and hierarchical models (D3)
- Develop and manage data sets (D4)

Introduction

Data will form the foundation for understanding and making decisions about digital built Britain. We need the capability to understand the value of this data and specify its use, to manage its access and security, to maintain quality and provenance and to share it with the right people in the right ways.

Companies will need to develop their management processes and policies to deal with more advanced software tools and the underpinning data and information. Artificial intelligence will have an impact – but where and what will that impact be?

In light of the tsunami of data[1] that will be generated by digital built Britain, what new capabilities do we need to catalogue it, make it discoverable, make it interchangeable and interoperable, and maintain its quality over the life of the asset or service to which it applies? The structures and schemas required to make data and models interoperable will enable new value creation opportunities and support collaboration between the parties involved.

To improve our understanding of digital built Britain and, especially, the move to greater integration between assets and services, we need to develop the capabilities to build and use computational models and data-based tools. The UK must develop its skills in these areas, building on BIM and

[1] For an interesting discussion of how metaphors for big data shape the way we think about it, see (Awati, 2015).

today's computer-aided tools for facility management. We need to ensure continuity by creating models that can be used by others with confidence after the model's creator has moved on to another contract.

We need to explore how we can combine models of assets to examine not just a single building but a block of buildings, a neighbourhood or a city. Coupled with models of the transport system and other essential services we envisage the use of large-scale digital twins as suggested by the National Infrastructure Commission. Capabilities needed include the capacity to store, find, access and share data and models in ways that maximise utility while preserving security and property rights. We need to integrate models of services with models of assets in ways that will enhance decision-making.

Technologies continue to be developed across a range of sectors, from the Internet of Things, to low-power, wide-area networks, to machine learning. These technologies have applications in the built environment, offering new ways to gather and analyse data and information.

New capabilities will be needed in order to make best use of the increasing power of data and models to review the past and to predict the future. Access to data and tools must be managed, recognising the power that access confers. Managers will need to embrace the use of models for the management of services and assets, in much the same way that budgets are used to predict financial futures and to prompt management action.

D1 Embed models and data as tools in understanding and decision-making

There are many benefits from embedding models and data as tools to foster a deeper understanding of digital built Britain, especially of its more complicated and integrated aspects, and then to go on to make better decisions. And throughout this, being able to articulate how good is the evidence, and the understanding and hence how robust is the decision. Extracting these benefits arise from the capabilities discussed below.

- Use a hierarchy of models to manage services, assets and transactions (D1.1)
- Develop organisational processes (D1.2)
- Explore Model-Based Systems Engineering (D1.3)
- Manage security, liability, risk and intellectual property (D1.4)
- Manage the implications of personal / occupant data (D1.5)
- Make decisions with greater use of data, information and models (D1.6)

D1.1 Use a hierarchy of models to manage services, assets and transactions

The decisions that will be taken about digital built Britain will depend upon the quality of the understanding that decision-makers and other actors have about their environment. That understanding is built by collecting information and building **models** of the world and its interactions.

The foundation for such models is people's **mental models**. People create and use mental models to simplify the richness of the world, to think through cause and effect, to predict the future and to make decisions.[2] 'Reasoning is a simulation of the world fleshed out with our knowledge' (Johnson-Laird, 2010).

Prior sections, especially about articulating value (V1), discuss the need for frameworks to act as tools for thinking and for sharing understanding. In essence, those frameworks help to make mental models more explicit and so make theories of change – and of cause and effect – sharable, discussable and negotiable. Furthermore, there is always a need for compelling evidence based on sound data and information. These mental models can be interrogated in order to decide which data points should be sought. The evidence can be discussed for its capacity to support or contradict current models and current understanding, enabling both to be confirmed or refined and developed. This improved understanding then underpins the capability to make better decisions. Decisions can be reviewed to evaluate what data was used and what additional data could be sought, measured or modelled. Management or service processes can similarly be reviewed in the light of the capacity of data, information and models to improve process performance.

If well-articulated mental models can be construed as representing people's understanding of how the world works, then computer-based models are yet more tangible incarnations. The algorithms describe cause and effect while the parameters set the leverage between elements of a deterministic or statistical model. Hence use of models encourages people to surface assumptions and to clarify beliefs and understanding.

This document presents a vision of the world where we will model many more aspects of digital built Britain. For example, **models of built assets** will be used to represent their current state in ways that make it easy to understand, while historical data will be used to refine and develop such models. Virtual reality tools based on model data provide ways for designers to communicate intent and potential vividly and persuasively[3]. There is likely to be greater use of computer models, with well-marshalled and presented data and information, and much greater use of monitoring to check what is happening in real time, exemplified by digital twins (D3). Meanwhile, much more use will be made of dynamic models that can simulate the future behaviour and performance of built assets.

Similarly, the development and management of services embedded in and delivered though the built environment can be improved based on both static and dynamic **service models**. Models will be created of the services, showing their current operation and predicting their future performance. Such models will be tightly coupled with the models of the built assets. For example, planned changes in a shopping mall can today be coupled with models of pedestrian behaviour to predict

[2] 'Each of us uses models constantly. Every person in private life and in business instinctively uses models for decision making. The mental images in one's head about one's surroundings are models. One's head does not contain real families, businesses, cities, governments, or countries. One uses selected concepts and relationships to represent real systems. A mental image is a model. All decisions are taken on the basis of models.' (Forrester, 1971)

[3] Identified by the Vision Network (Vision) as an appealing use case of recognised value today.

footfall past shops. Models of railways and roads predict likely service levels and are used for operations management. This modelling will extend much further in the future, for example to integrate service models with Building Management System models to optimise cost and carbon emissions.

Beneath all of this, the continuing collection of data and information and its comparison with the predictions of the models will enable us to improve the models, increasing our confidence in their fidelity and representativeness. Note that today, in many cases, the same data sets are being collected by owners and operators of assets and by service providers depending upon those assets, albeit at different time horizons and levels of fidelity (UIL b, section 3.3.3). CAR (p. 22) explores capabilities needed for the future and specifically flag the importance of 'keeping an updated model and creating a single source of truth' as the foundation for this integrated set of models. A single source of truth promises to ameliorate problems arising from the duplication of data by owners and operators, including the risk of inadvertently accessing inaccurate, outdated or anomalous data during the construction or operation of built assets and dependent services.

Built infrastructure is expensive, so **financial models** exist to predict costs and revenues. In a future digital built Britain, such models will be tightly linked to computer models of both the built assets and of the services based in the assets. These linked models will then allow exploration of the value and costs of change, tighter management of operations and credible pursuit of optimizing though-life costs and benefits. Turner Harris describes this as 'Real-Time Reporting of Utilisation & Return on Investment'. In essence, this becomes a model of the business (TH, p. 38).

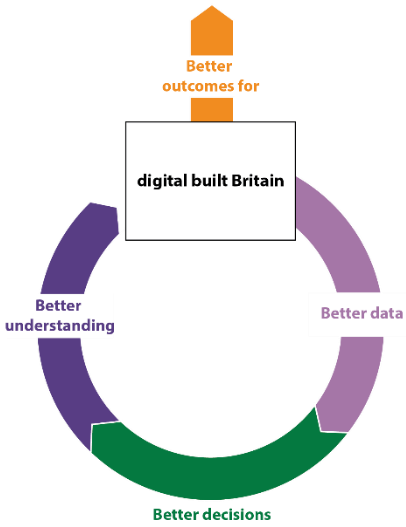

Figure 3 - Better data enables better outcomes for digital built Britain

These computer models, linked together in ways that are ever more sophisticated and seamless, then offer policymakers, decision-makers, users and investors a way to explore their world and build a better understanding and deeper insight. These insights respond to the questions discussed in V3. How will maintaining a building today affect the services of tomorrow and the benefits for the future? Will a cost today be repaid in future? What action seems to have the greatest benefit for least cost? How do investment strategies change if the definition of 'cost' or of 'benefit' expands to incorporate social and environmental costs and benefits? As our built environment, services and organisations become more interlinked and more integrated, it will become more important, and more difficult, to understand the ripple effects of actions. Intuition will no longer suffice, and computer models will help build understanding and insight, especially about integrated services and infrastructure systems (G4).

The ability of a computer model to explore alternative futures and predict outcomes makes it ideal to explore decision alternatives and make better choices, so such models will be at the core of decision-support tools. And with actions chosen, plans made, and interventions begun, such models enable evaluation and monitoring of progress against the plan.

The starting point here will be about mindsets in the organisations, and especially the need for policymakers, decision-makers and managers to explicitly seek insight and support from modelling tools in general. Digitalisation needs to become part of the fabric for organisations, their processes and structures and the implications of and need for this capability are explored and explained by Turner Harris (TH, p. 44). In a world of accelerating change, such data, information and models become part of the corporate memory, and the customised processes become part of corporate competitiveness.

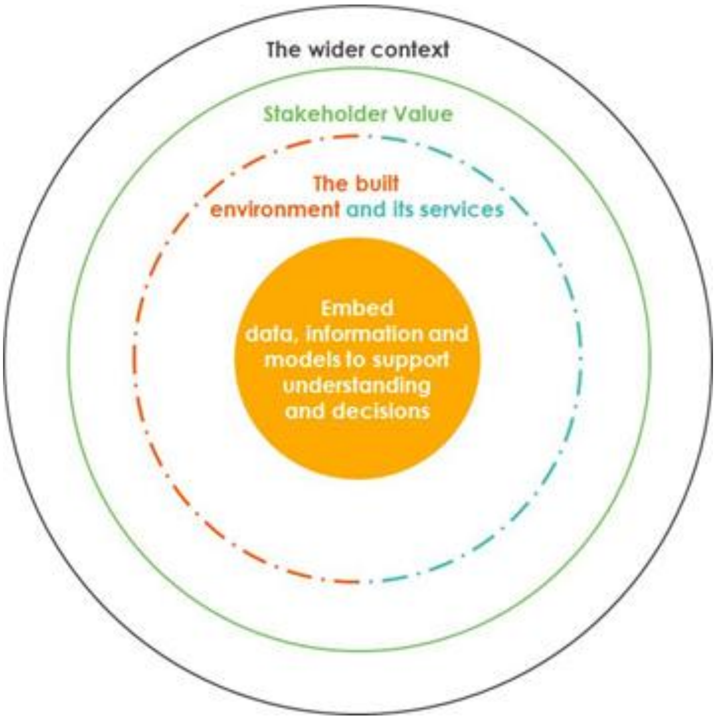

Figure 4 - Data, information and models sit within a broader context and therefore must be embedded in those contexts through culture, processes and structures

Much of what managers will want to know about digital built Britain will not be measurable (see V1.1). However, models can be used to infer the unmeasurable. For example, while we cannot directly measure the heat wasted from a building, we can model it and use that as a proxy for understanding the magnitude and nature of the issue to decide whether and when to act.

Those responsible for the construction and operation of built assets need to develop better mutual understanding of the requirements for data to be transferred during handover (CAR, p. 23). Many, especially when working in collaboration across the life of built assets (B3), seek a 'single source of truth', or at least an 'authoritative source'. Managing data in such a way that it can be declared and then shared as such offers considerable benefit. Doing this internally depends upon robust management policies and tools and on agreed structures and schemas (D2) by which data quality and interoperability can be assured. Doing so across organisational boundaries requires equivalent structures and schemas, albeit with greater demands for robustness and consensus about interfaces.

Data and information may have value in their own right. While this value will need to be justified within the context of a business model (V3), shared information may be a tradeable commodity, and the value may be greater, depending upon the user's purpose. Underpinning structures that enshrine consensus views about interoperability (D2) will be critical here.

Models of different parts of a system can be federated to provide tools to explore interactions. These might be interactions between sub-systems that make up a broader system, for example how an air-conditioning unit interacts with insolation in affecting building temperature. Interfaces between models of infrastructure and models of systems will become increasingly important as operators of both try to understand the interactions (S2). Models may even be stacked to model the utilization and even the business return on investment, as mooted by Turner Harris (TH, p. 38).

Early use of models holds out the promise of exploring, at low risk, more ambitious designs for services and service-asset interactions which may ultimately lead to significantly higher performance and benefits. Developing these capabilities could provide an antidote to very understandable conservatism observed today (UIL b, Section 3.4.4). Some organisations, especially in aerospace and defence have embraced models completely, embarking upon Model-Based Systems Engineering. There is much to be learned from these sectors (Madni, Madni, & Lucero, 2019) and work beginning in the AECO sectors (Chatzimichailidou & Whyte, 2018). Other industries have adopted digitalisation enthusiastically, giving rise to the term Industry 4.0. However, there are undoubtedly characteristics of the construction industry which will impede adoptions. A survey of Industry 4.0 concepts and their potential adoption (Oesterreich & Teuteberg, 2016) identify three promising clusters of opportunity: the smart factory, simulation and modelling, and digitisation and virtualisation. They go on to identify barriers and benefits, largely aligned with the findings of CAR (CAR, section 3.3.4).

One could envisage a maturity assessment framework to assess organisation's progress in adopting and using models. One such has been proposed for digital twins[4] and this could be developed as a tool. This is similar in nature to the FOuNTAIN Network's proposal for a maturity indicator for companies' use of data and information (FOuNTAIN, section 2.2).

Feeding data and insights along the value chain enables decision-makers to learn from previous practice. This is the 'golden thread of information' advocated by Dame Judith Hackitt (2018b), in which information flows forward through a built asset's lifecycle to ensure that information about design decisions, refurbishment, materials and so forth are captured and managed. This helps subsequent stewards of that asset to make better decisions because they have greater contextual information and insights to go with the data and models they inherit.

Information flows in the opposite direction will also be powerful in digital built Britain. Facility managers can feed back information to contractors about what data and information management practices they would have found beneficial. Contractors can do the same for designers, and so on, up value chains and supply chains. At the end of a built asset's life, feeding insights from whole-life data back can help ensure that higher performing assets will be built in the future. A review of the current literature can be found in (Rasmussen, Jensen, & Gregg, 2017).

With data and models well-managed, it becomes possible to link them to other decision support tools, for example, linking BIM with computer-aided facilities management tools despite the many issues to be addressed (Gao & Pishdad-Bozorgi, 2019). Research has explored pilots in different contexts (Liu & Issa, 2012) and continues today,[5] but it is clear that there is much to do in acquiring and manipulating data to create the models, especially of legacy assets (see also Zou, Arruda, & Ergan, 2018 and section B3). Doing this will need capabilities in both the management processes and in the structures and schema (D3) at the interfaces.

[4] http://www.smart-energy.com/industry-sectors/business-finance-regulation/digital-twins-maturity-continuum-david-socha/
[5] http://www.ifm.eng.cam.ac.uk/research/asset-management/research-projects/infrastructure-digital-twins/

Data-driven decision-making is seen as a core capability for digital built Britain (CAR, p. 38). However, industry participants remain concerned about the trust that can be placed in data sets and are concerned about investment in tools that might be overtaken by technology change (*ibid.*, p. 38).

D1.2 Develop organisational processes

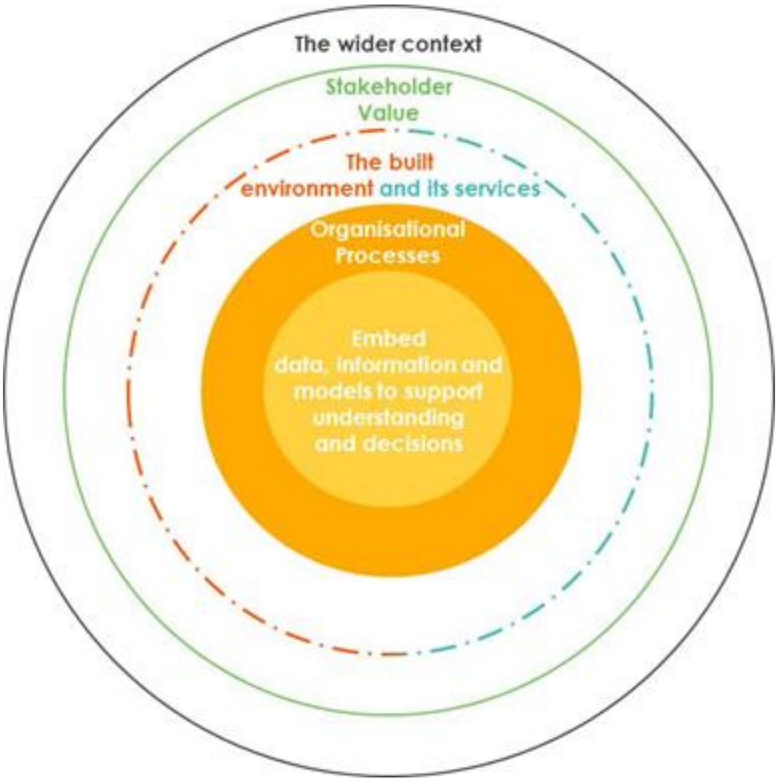

Figure 5 - Organisational processes mediate between the use of models to make decisions about the built assets and services they describe

Organisational processes serve several purposes; as repositories of shared knowledge about efficient and effective ways of working, and as safety nets to protect value; in this instance covering not only the value of data and intellectual property, but also reputation.

Organisational processes set the context for the use of data, information and models in developing improved insights and better decisions (see *Figure 5*).

Organisations aiming to integrate the use of data and models will need to be able to create the internal governance structures that support the processes and articulate and enforce the decision rights, authorities and responsibilities associated with the creation and management of the data and information within the toolsets. This thinking is a logical extension of that in BS 1192 and ISO 19650 (UIL a, p. 59).

There are several capabilities here that are managerial in nature and will be embodied in the specification of data and the operation of models within the organisation. These include:

- Managing and maintaining data, information and models in ways that recognise their value, not only for the owner of the built asset but also for service providers dependent upon the asset
- Using processes, tools, governance, etc. to maintain the fidelity and consistency of the data, information and the models to maximise the alignment of the models with those of the asset they represent (through-life)
- Managing the growth of models from multiple data sources and over the planning, design, build, operate and integrate cycle of the built assets they represent to ensure that performance, quality, security, interoperability, discoverability and other attributes are maintained

- Managing security of and access to data and models, for commercial reasons, to minimise the risk of malicious attack and to maintain robust and secure service provision (UIL b, section 3.3.7)
- Managing security and access of data to manage concerns about ethics and privacy
- Managing model access and decision rights across a diverse project team and across an ecosystem of supply chains and service providers
- Assessing, labelling and managing data and information with respect to the assured validity of the models and their projections
- Managing the integration of models into federated models of deeper and more complex systems while tracking the development status, robustness and uncertainties of each component model.

It is important that the commercial value and liabilities associated with the data and models associated with the service and business, be fully understood. Doing so enables the data and models to be objects of commercial transactions in their own right (UIL a, section 4).

In a report for the National Infrastructure Commission, Deloitte (2017b) recommend the creation of a guidance framework, much of which is being picked up by the DFTG with tasks that appear on their roadmap (Enzer et al., 2019). The Deloitte document suggests guidance in management processes as well as in data interoperability, which may be an extension beyond the focus of the DFTG.

Process models and the tools to deliver them in different contexts will be bespoke in their specifics. Most companies will align their processes with the established process frameworks, including

- Construction Industry Council (CIC) Scope of Services
- RIBA Plan of Work 2013
- PAS 1192
- Government Soft Landings

It is almost certain that there are examples and lessons that can be transferred from sectors such as aerospace and defence, shipbuilding, chemical process industries and oil and gas. This should be explored and undertaken. Research illustrates the prime issues and proposes candidate frameworks (Alreshidi, Mourshed, & Rezgui, 2016), while the need to address these topics is recognised as tasks within the DFTG Roadmap (Enzer et al., 2019, Tasks 2.7-2.9).

Some organisations may choose to adopt a relatively formal approach to management process development, and a valuable way to explore the potential for enshrining data and models will be to explore in detail the process maps that show the decisions to be made throughout the asset's lifecycle and, importantly, throughout the service processes. This is part of a broader drive for ICT support to business processes (Susanto et al., 2019) and a broad opportunity in the sector, also noted by the FOuNTAIN Network (FOuNTAIN). Tools such as Business Process Model and Notation (BPMN) and Decision Model and Notation (DMN) are well established and research continues exploring the integration between processes and decisions (Hasić, de Smedt, & Vanthienen, 2018) illustrated by a plethora of case studies of the application of ICT tools to all activities in the sector (Adwan & Al-Soufi, 2018). 'Process simulation' is an emerging topic of BIM research, especially among Asian research centres (Badrinath, Chang, & Hsieh, 2016), highlighting the importance of linking models with management and governance processes within and across organisations.

The transition between manual and automated business processes and the growth of workflow automation has been accompanied by a proliferation of digital process automation philosophies and tools on the market. Furthermore, implementing such systems places a premium on the standardization of the data protocols and interfaces to be used.

Products with features such as decision trees, process design and simulation, automated performance management etc. may deliver value, or may be a costly investment with little return. 'There is no single process automation technology that satisfies every scenario within an organization. Without using a guiding selection framework, application leaders could choose a product that is poorly aligned to their use cases resulting in suboptimal benefits.' (Ray, Dunie, & Guttridge, 2019) Adoption also requires those using decision support tools to bring external perspectives to bear (see ***Box 3*** for an example).

Box 3

Acquiring and managing quality data alone does not guarantee that the target outcomes will be met. At the 2010 Abu Dhabi Formula 1 (F1) Grand Prix, Ferrari had one of the world's most advanced data and information management systems for decision support, and yet the surrounding strategies and processes led to a bad decision that may have cost them the World Championship that year. The crucial decision rested with the team's Chief Strategist sitting at the pit wall, an informational hub fed with models relayed from a remote data analysis centre. The decision process was set up to enable rapid decision-making in a high pressure environment, and the Chief Strategist was only given two choices by the decision support system and, according to the team's procedures, was required to select one of these two options even if he could see a better third option.

Aversa, Cabantous, & Haefliger (2018) point to this, among other structural issues – such as a process that did not allow for input from people who could see the conditions of the race and may therefore have pertinent insights excluded from the data – as contributing to the outcome despite the high tech decision support system. This points to the need for decision frameworks that do not over-rely on data and that enable experienced professionals at various levels of an organization to have input in the eventual decision. It also points to research topics about the socially situated nature of data driven decision-making, and the relationship between decision support tools and structural mechanisms such as procedures, frameworks and processes.

In many ways, this mirrors the experience of other industries in adopting product lifecycle management (PLM) tools and work in this area explores the implications for AECO and the lessons to be learned (Aram & Eastman, 2013). Developing this area will always be specific to the needs and priorities of individual organisations, but making guidance available may accelerate the process across the spectrum of UK companies.

The whole area of design informatics was reviewed by (McMahon, 2017), who highlights several significant areas for development. Of particular relevance as sectors converge in digital built Britain is the need to better understand how better to use models, how then to design tool chains and how to avoid the traps of domain-specific models and data. This is especially important in the face of more complex and nuanced needs to synthesise options that meet ever wider ranges of design objectives, while remaining resilient, effective and efficient. This, then, is a topic in which research could contribute to the debates about design tools and their use, and provide guidance to sector participants about how to best address these issues.

McMahon's work (2017) resonates with issues identified with data from built assets, specifically the difficulties of working with semantic data. Above all, though, the primary need is for enhanced interoperability of data and models in order to better represent the multiple viewpoints that need to be combined in effective design. This will become even more important as we move to though-life issues and the issues that arise from the interaction of services and their supporting assets.

Some processes are early candidates for development. For example, the Vision Network (Vision, section 3) reports that design support and design review processes have been explored as targets for the adoption of immersive technology and its supporting models. Processes and practices in these areas can be developed to facilitate co-creation of ideas, greater exploration of options, and active exploration of problem areas using models. All these opportunities have been shown in demonstrators explored by the Vision Network (*ibid*., section 5.2). Indeed, Anglian Water's @One Alliance have incorporated VR into their workflows, enabling smarter design thinking and aiding better collaboration, and an example of the process developments around the tools themselves. In a further example, D-COM describe a scenario to illustrate the fundamental change in organisational processes that are enabled and required by automated compliance checking (D-COM, section 2.2).

Other research in this area explores the implications of digital integration and organisational change and for the practical change management required (Çıdık, Boyd, & Thurairajah, 2017). Such strands of work augment the exploration of both processes and value by recognising the change implied.

D1.3 Explore Model-Based Systems Engineering

For those organisations that wish to embrace the use of models to underpin their philosophy of work, the leading edge today is Model-Based Systems Engineering (MBSE). This approach and its component tools and processes are well established in industries such as aerospace, defence and the chemical process industries, especially where virtual assets and digital twins are already in widespread use (Madni & Sievers, 2019). It is not, however, second nature across those working in the built environment. This is changing with the creation of the Systems Engineering Toolkit for Infrastructure[6] and the work of Chatzimichailidou and Whyte (2018) at Imperial College.

Figure 6 below, from Madni et al. (2019), provides a simple graphical picture of MBSE applied to a digital twin, and the paper from which it is drawn provides an accessible introduction to the area.

[6] https://wwwf.imperial.ac.uk/blog/csei/2018/04/23/introduction-to-the-systems-engineering-toolkit/

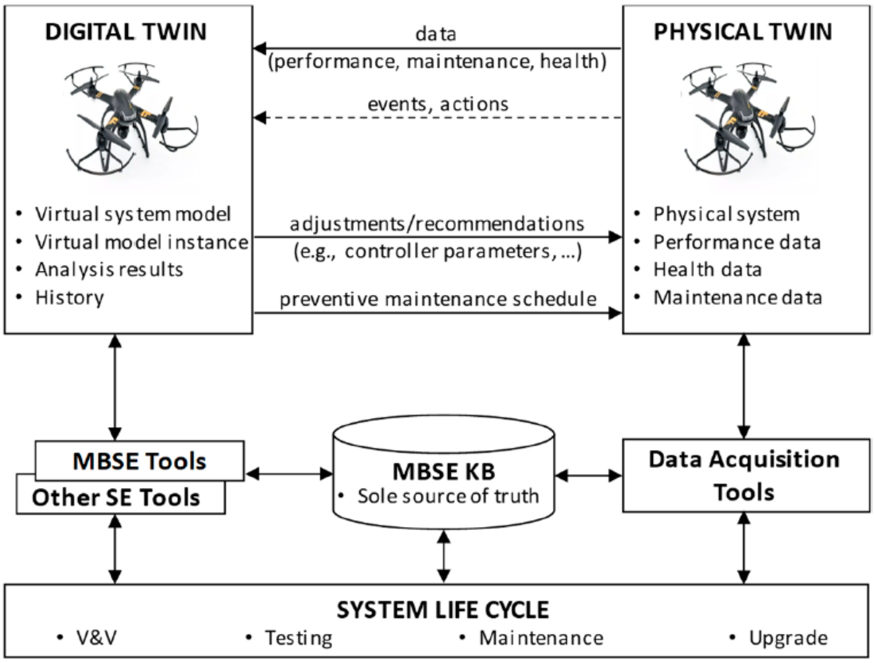

Figure 6 - Digital twin concept within an MBSE framework (source: Madni, Madni and Lucero, 2019)

The move to model-based engineering is encountering issues associated with intellectual property management and management of the uncertainty of data, information and models, and those outcomes. Others have explored these and similar issues, for example within the context of the US Department of Defence initiatives (Reid & Rhodes, 2016), but there remains much to be done to develop pragmatic guidance to help companies embarking on the journey through and extensive use of models.

The adoption of MBSE could be explored as a route to better performance across the sector, building on the insights, experience, tools and technologies of others (Fitzgerald et al., 2016; Whyte, 2016). Groups such as those at Imperial College,[7] at Loughborough[8] and at Newcastle[9] are among the candidates to conduct research into what is needed to adapt the lessons and experience into the domains relevant to digital built Britain.

D1.4 Manage security, liability, risk and intellectual property

A key part of the value derived from processes is the assurance function: assuring compliance with prevailing legislation and helping the organisation to protecting value in the security of data, maintenance of confidential information and protection of intellectual property.

[7] http://www.imperial.ac.uk/systems-engineering-innovation
[8] https://www.lboro.ac.uk/research/cice/
[9] http://www.compass-research.eu/

Those who develop and enforce processes and policies in the use of data, information and models will need to carefully consider and manage permissions, access and security. This will become a yet more important capability as built assets become more tightly entwined with the services they enable and support (UIL b, section 3.3.7). Along with processes and policies, organisations will need to build a culture of security-mindedness (Centre for Digital Built Britain, 2019). This will also need to be part of the portfolios of competence (L2) of individuals within digital built Britain as well as professionals working with data and models.

While the National Cyber Security Centre (NCSC), the Centre for the Protection of National Infrastructure (CPNI) and other government organisations have flagship roles in developing the UK's capabilities in managing the security of data and information related to critical national infrastructure, there is a broad ecosystem of stakeholders, including individuals who manage or have access to sensitive data through their jobs.

Sharing data – while key to unlocking potential value, efficiency and social outcomes – also opens the built environment and the people in it to a range of security concerns. To balance security concerns with the need for openness, organisations need to define and manage potential liabilities and risks arising when data is shared (SW – Data; UIL, 2019, p. 79). The standards document addressing security-mindedness in smart cities clearly outlines one of the chief data and information security problems for data and models: 'Within a smart city, any organisation which holds, or has access to, sensitive data or information but has a lesser degree of security around its systems than other organisations with the same access, is more vulnerable to attack. If such an attack were to be successful, a security breach or incident damaging to the city as a whole could result.' (PAS 185:2017) Cyber-security is a particular issue when considering fragility that might propagate along a supply chain (TH, p. 22).

The key here is to think in terms of a spectrum: 'Rather than rely on an open/closed distinction, data access should be seen as a spectrum, with different degrees of data openness. … Given that the circumstances of data will change with each use case, decisions regarding open data should therefore be made on a case-by-case basis.' (HM Treasury, 2018)

Design of processes and systems needs to be weighted by the appropriate level of security for the scale of the risk. Those who manage or occupy a building may need a detailed and robust security plan, or they may only require a light touch approach. PAS 185:2017 outlines a risk mitigation decision process that could be deployed at any scale, and emphasizes the need for clear governance, for staff participation in secure behaviour and for rehearsing responses to security incidents. However, it will be important to consider the security performance along the entire supply chain and network of interacting partners.

Codes of Practice have been developed in order to provide structured guidance about security and safety in ways that are comprehensive and aligned with the lifecycle. For an approach to the creation of such codes see Bloomfield et al. (2018), where lessons from the rail and automotive sectors may contain valuable lessons.

Other areas that will require organisations to develop capabilities will be around the management of the commercial value of confidentiality and of intellectual property enshrined in data, information and models. This is a specialized domain and likely to grow in complexity as new opportunities emerge, for example distributed ledger technologies. Research that predicts issues before they emerge could serve by creating appropriate guidance for development of processes.

D1.5 Manage the implications of personal / occupant data

With the integration of services and the built environment, so the concerns and considerations associated with data about the public, with data ethics, and with the issues of handling of 'big data' will become as relevant as today's concerns about asset-specific data, which is characterised by lower rates of change and longer relevance. In particular, as digitalisation of the built environment offers ever more sensor technology and potential for monitoring users of buildings and infrastructure services, so organisations need also to consider ethical issues. See also section B3 on smart asset management for a discussion of the opportunities in monitoring building occupants to develop building performance.

In the post-GDPR world many organisations are fearful of sharing data. However, data privacy legislation does not preclude sharing. Rather, it seeks to protect data subjects from unethical uses of information about them. Organisations, institutions and professionals should ensure that they understand how data ethics legislation effects them and their pathways to legitimate, ethical information sharing, as well as embedding this understanding in the design of information management processes. Particularly where personally identifying data is collected in the built environment, issues of consent appear, particularly around using the data only in the ways to which the subject provided consent. The boundaries of this have yet to be explored for digitally-enabled buildings. For example, by entering an office building one is, perhaps, tacitly consenting to their image being recorded for building security, but if facial recognition is applied and that data is shared outside of the context to which they consented, what would be the legal recourse?

Further research is needed into the ethics of big data sourced from multiple organisations, particularly with regards to the ability of big data to de-anonymise individuals or assets, and the use of analytics to make inferences about individuals or assets. The mechanisms for enshrining and enforcing data ethics may vary. In the UK, Information Commissioner's Office (ICO) oversees enforcement of data legislation and levies punishment in cases of breaches of privacy, while Nersessian (2018) suggests that international human rights law might set the global standards for data ethics. This would be beneficial to information management in supply chains that span international borders, ensuring that all partners are working toward the same basic understanding of ethical data use. The Open Data Institute, the Alan Turing Institute and independent organisations such as doteveryone are contributing to the agenda for ensuring that ethical practices around data and information are enshrined and enforced in various areas of public life. These will need to be reflected in the governance and use of data and models.

Big Data Analytics is, of course, a rapidly changing domain and the leadership of the research agenda will come from outside the AECO sectors. Complex organisations that rely on accurate sharing of information and data, include the National Health Service[10] and the police force[11]. The complexity and diversity of these organisations makes them potential sources of lessons and insights. Akter et al. (2019b) survey this space for service systems and confirm the rate of change of methods and tools-sets. While they suggest a straightforward process, they identify the primary issue as embedding analytics within corporate decision-making.

All this becomes increasingly challenging as the scale and homogeneity of data increase, for example, as it is shared across supply chains, joint ventures and other partnered organisations. Data and information are context-dependent, and big data leads to a degree of homogeneity in which it can be difficult to retain the data's specificity, relevancy, presentation and descriptiveness, even if such attributes were achieved in its original context (Ghasemaghaei & Calic, 2019). Additionally, data and information that are shared across organizational boundaries must meet the criteria of all relevant organisations in order to be useful. For example, if a building manager captures data about air temperature over the course of the day but does not need the measurements to be particularly accurate, they may use a scale that suits their need. However, if they share the data with someone researching energy use relative to ambient temperature, the data may not be granular enough to be compatible.

Meeting the requirements of the individual asset versus all other users of that data is a complex balance to strike, and managing this complexity is a defining characteristic of sharing and reusing data (Stefanowski, Krawiec, & Wrembel, 2017). It is the responsibility of all organisations involved to manage the quality of data 'in all steps of data processing and analysis including the initial data collection, data storage, data retrieval, and data preparation for analysis' (Ghasemaghaei & Calic, 2019). This means that explicit criteria should be set out at the beginning of a collaboration involving shared data to define the standards that are needed to meet decision-making needs, and subsequently be enshrined in the data governance layer for all interdependent models and process tools.

Given this intersection of data, information and models with such different characteristics, and the novelty of this for companies in the AECO sectors, research could be usefully undertaken to gather and transfer relevant lessons, not only from the industries characterised by high-value assets, but also from other sectors working with user data in larger volumes.

D1.6 Make decisions with greater use of data, information and models

Better decisions, founded on better understanding will be underpinned by better use of data, information and models. Better decision-making needs, however, to be founded on know-how in several key areas: for example, in understanding the implications of uncertainty in data and parameters, and in deciding how to manage the scope and budget of underlying analyses activities.

[10] http://www.england.nhs.uk/ig/about/
[11] http://www.app.college.police.uk/app-content/information-management/management-of-police-information/common-process/

Both topics are discussed further in the section on decision processes (G5). Communicating nuances of contentious decisions to multiple stakeholder groups is also addressed there.

Within organisations, the primary need is to choose appropriate tools and then to utilize them effectively. Without this, investment in data analytics does not pay off.

> *'Only 27% of firms reported that their investment in data analytics has been successful. One reason for the failure is that many firms still do not know the necessary conditions they need to utilize data analytics tools effectively. Existing research focuses on anecdotal evidence about the impact of data analytics usage on the quality of firm decisions and there is a lack of understanding about the conditions required to improve firm decision quality through utilizing data analytics tools.' (Ghasemaghaei, 2019)*

Hence, the focus here is on issues around organisational processes and on the implications of building better organisational decision processes based on models and data. Part of the process and culture design that will be needed is in support of dialogue between analysts and decision-makers (PUN, section 1.2), especially if widely separated in seniority, place, time or culture. There is a barrier to manage here. 'It is widely held that analytical people don't communicate well with decision-makers, and vice-versa. As a result, analytical capabilities may not get used effectively, and decision-makers may fall back on their intuition or experience.' (Davenport, 2013) This indicates a learning and adaptation need for analysts (see L1), and a need to develop decision support tools that are more intuitive for decision-makers while still communicating limitations and provenance of data.

This section deals with several data attributes and factors that can influence how well it enables accurate insights and better outcomes:

i) Data bias
ii) Data quality
iii) Uncertainty
iv) Communicating decision outcomes

i) Data bias

Data is not a set of neutral facts free from human subjectivity, nor is it exhaustive. Data quality will impact the insights generated by digital tools. Flaws introduced during collection could dramatically shift the quality of information used to drive decisions and actions, and there are limitations that can arise before and during capture. First, decisions are made about what the phenomenon of interest is and what is considered 'data' within that phenomenon. Limitations to what *can* be recorded, e.g. what current sensor technology is capable of, and decisions made about what *is* recorded further limit the data set as originally collected (Jones, 2019). This means that the representative power of data is limited by its own creation. Organisations will need to explicitly make decisions taking into account the quality (in the widest sense) of the underlying data, either used directly or used to create and manage models.

The purpose for which data was collected and its context may undermine its relevance or usefulness in decision-making, in querying the data or in deriving insights. Data is rooted in a particular real-world context, and it is not necessarily appropriate to apply data collected in one context to another. 'What managers, data scientists, and social scientists think of as data is in fact not given. It is the outcome of a process of measurement—an interaction between an observer, a technique or apparatus, and a context' (Moldoveanu & Reeves, 2018). Organisational processes must support users in exploring such limitations and validating the data they intend to use.

ii) Data quality

As digital built Britain unfolds, so the variety of data sources available and used will increase. This can only accelerate with the roll-out of IoT sensors operating at higher data rates over wireless networks. Managing data quality and, more importantly, being aware of the implications of these technologies becomes critical. It is unlikely that companies in the AECO sectors will take a lead in research and technology development here. However, organisations that are adopting the new tools and data sources will need an awareness of their strengths and weaknesses. Processing, cleaning and anonymizing data can also introduce issues with accuracy, relevancy or descriptiveness of the data. Current research, for example with smart connected products, provides a starting point. This research is attempting to identify the issues and practices for managing data quality and highlight, for example, degradation of sensors, environmental interference, vandalism, security vulnerability or data stream processing (Perez-Castillo et al., 2018). Such overview work can be adapted for applications specific to digital built Britain and developed as guidance to accelerate good practice.

Others point out the concerns associated with trying to run digitalized portfolios of assets alongside non-digitalized legacy assets, the triage process of deciding when and how to invest in digitalization (TH, p. 5), and the risk of losing corporate experience and memory. While there is great promise in adding information alongside the data, it is not yet clear how this might be done in ways that make it usable in practice. Other industries which have explored the development of tools to do just this have already engaged with difficult issues (Bole, Powell, & Rousseau, 2017) and there is much to be learned from such experience.

iii) Uncertainty

Uncertainty of data and of parameters within the models will need to be understood; both its source and its implications in decision-making. Decision-makers will need to recognise the implications of data uncertainty (G5) in reaching conclusions and even in building a robust understanding the real state of the assets under management (CAR, p. 24).

The Uncertainty Network captured this well in their report (Uncertainty):

> *'There is a pressing need among stakeholders for improved quantification of uncertainty in the relationship between model outputs and predictions, and equivalent quantities in the real world. Specific issues include unmodelled aspects*

> *in complex systems of systems; hard-to-quantify issues such as intangibles and externalities; improved capability to develop logical arguments based on scenario studies; the use of modelling to de-risk contracts; and developing more efficient and robust engineering standards and regulatory incentives, which must deliver good outcomes in a wide range of circumstances.'*

iv) Communicating decision outcomes

Finally, there is the matter of communications around decisions and the tools used to reach decisions. One aspect of this lies in the data and model visualisation tools that are used to make the data and models more accessible. This has become an issue in immersive technologies, where the usability of tools to make decisions is under investigation (Vision). Sophisticated organisations may choose to manage their own visualisations of data analytics[12], but the vast majority will use tools and techniques developed elsewhere, leading to similar context issues as discussed with data bias.

Communicating decisions also needs attention (G5). As well as the decision itself, it is often useful to communicate the robustness of the decision and the uncertainties inherent in it. Cautious stakeholders may demand an explanation of such robustness questions. National and international government bodies responsible for statistics have some of the clearest guidance and regulations for communicating uncertainty. For example, the European Food Safety Authority has produced a thorough guide to communicating different levels of uncertainty to different audiences (Hart & others, 2019), while the UK's Government Statistical Service has published a report on communicating quality, uncertainty and change (Quality Centre and Good Practice Team, 2018).

All of this is a natural extension of evidence-based decision-making, a topic well covered in the policy literature. Some guidance specific to the built environment exists (Criado-Pérez et al., 2018), but many who have been consulted in the development of this document feel there is room for improvement.

The FOuNTAIN Network (section 2.2) recommends the use of information management maturity measures to help organisations identify where they are on the journey. The Network notes that there are several such maturity scales and recommends that there be one built into the standards regime.

Although much of the push for developing new organisational processes arises from new digital tools, more data and greater us of models, the final competency needed here will be change management, as people and organisations learn new tools and data to new realities. It is said that 'People often cling to their existing working practices and processes. Reimagining value delivery is especially challenging as employees move from conceptual levels toward practical implementation on a still-evolving digital platform.' (Miers & Kerremans, 2018). Hence, there is considerable crossover with Learning and Adaptation (L2).

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[12] 'Analytics should be consumable, and best-in-class organizations now include designers on their core analytics teams.' (Mayhew, Saleh, & Williams, 2016)

In summary, then, to extract the most value from the greater availability of data and information and from the massive potential of digital tools in underpinning better understanding and better decisions, organisations need to embed the concepts within organisational processes and behaviours, and then adopt and adapt the tools to their situation and skills. There is much research and huge amounts of prior experience form adjacent sectors available for advice and guidance – but each organisation will need to build and embed its own capabilities (L2).

D2 Develop and manage structures, schemas and tools

Central to the whole topic of data and models is sharing them in ways that are seamless, automated and cost-effective. Therefore, a key capability is the creation and agreement of frameworks for data and information that will allow data to be shared between models, between organisations and, inevitably, over an ever-richer set of application domains. The ease with which this can be done underpins transactional efficiency; a fact that is not always appreciated (UIL a, section 3.3.6). This entire topic area is a focus of attention of the Digital Framework Task Group, identified within the 'Commons' thread on their Roadmap (Enzer et al., 2019).

The data frameworks need also to be able to accept data from various sensor and measurement systems and feed it to various decision support tools. Interfacing this variety of sources and users requires the capability to agree and create frameworks for data sharing and the standards to underpin these frameworks. The matter of standards requires care to strike the right balance between achieving effective data interchange while not impeding innovation, a point identified by the FOuNTAIN Network as the 'capability to establish the appropriate scope, priorities and pace of standardisation, at *industry*, *project* and *organisation* levels' (FOuNTAIN, section 3.2, their italics). Other industries provide examples of pursuing the same objectives and there is a rich pool of resource to draw upon, exemplified by, for example, ISO 15926 (British Standards Organisation, 2003) and West (2010). (For more on standards, see G2.)

The creation of such frameworks is at the core of the work of the Digital Framework Task Group, and their roadmap lays out the constituent tasks to develop the capability (Enzer et al., 2019). With the framework in place, it is assumed that the commercial market will provide the data management environments, the data management tools and the modelling tools that will be used to build the asset-specific models themselves.

While a network of integrated models is easy to imagine, for example to represent several lifts within a building that is itself part of an integrated campus, the tools to create such networks of models, to manage the data flows and to help users extract insight and make decisions are some way from widespread use. If, however, system management is to be supported by federated models, these networking and integration toolsets will need to be built, together with the means to confirm validity and fidelity of data exchange and operation. There is not only the need to design such tools, but also to create the architecture of the portfolio of capabilities that such tools will deliver. Only with these tools envisaged, built, ratified and working together in a portfolio will managerial and operational users be able to use models to make better decisions about through-life management of real assets.

The introduction to this section mentions the potential integration of models of assets with models of the services they support. Together with this jump in complexity lie all the issues of independent organisations managing the services and the assets. Such scenarios have all the characteristics of a 'system of systems'. The implications of Model-Based Systems Engineering and the modelling, federation, validation, verification and use of such 'system of systems' tools is an entire domain in its own right, holding out promise of new capabilities, albeit only after considerable further research (Nielsen et al., 2015). See also the discussion of complex integrated systems (G4).

Furthermore, the use of integrated models will entail collaboration across several organisations and there will be a need for tools to underpin such collaboration and to help with data management, decision- and access-rights and with the security and confidentiality aspects of data, information and its management. Alreshidi et al (2018) have developed a specification document for a cloud-based collaboration tool as an example of the coverage needed. They also discuss the issues, barriers and drivers for the adoption of such tools in both governance and management of the data and models.

This section describes the underpinning capabilities that will enable the development and management of structures, schemas and tools for secure data sharing and better outcomes:

- Develop organisational governance frameworks for data, information and models (D2.1)
- Develop technical governance frameworks (D2.2)

D2.1 Develop organisational governance frameworks for data, information and models

Data and information management carries with it a series of trade-offs: between sharing and security; access and privacy; value for the organisation and societal value; clarity and comprehensiveness. Operational frameworks are needed for organisations to maximise the benefits and minimise the downsides inherent in these trade-offs. Governance tools such as standards are needed to align organisations within and between sectors in matters ranging from the details of information exchange to guidance on the ethics of information management. The capability to create standards (G2) and guidance for these frameworks should include the creation of the appropriate exchange mechanisms (FOuNTAIN, sections 3.2 and 4.2).

The FOuNTAIN network suggests that prescriptive management process models would also be of use to organisations developing their systems. Other elements of organisations' internal policies and processes may need to be developed for creating and fulfilling information delivery schedules based on industry and project protocols (*ibid*., section 5.4). These capabilities and their dissemination in guidance and standards will define, dictate and manage the quality, security, accessibility and many other attributes of data. Whether embedded in the enabling toolsets of a model, or enshrined in organizational process tools, guidance and standards will help to ensure that digital analysis of data and information generates valuable insights.

D2.2 Develop technical governance frameworks

There are already several data structures, schema and standards in use which underpin data exchange within the sector today[13]. These represent considerable investments and have constituencies that understand them in depth and use them commercially. However, for a variety of reasons these will need extension in future. For example, CAR (p. 22) note that there are no schema that manage the whole range of information relating to the functions of a facilities management department, that today's schema are insufficient for the deconstruction phases, and that decay data is not well-supported. Importantly, they also note that schema extensions could usefully encompass matters of uncertainty.

Another driver that will encourage the evolution of schema is the Internet of Things and the proliferation of IoT sensors across buildings. Already researchers have proposed open standards for interfacing IoT sensors into a BIM model based on current schema (IFC) (Dave et al., 2018). However, issues of interoperability, security and breadth of uptake are already seen as an issue.

The evolution of a technical governance framework will not be a one-off task but instead the UK will need the capability to develop current classification systems, schema and frameworks, in order to maximise the potential to share data, and in ways that make best use of current skills and investments (FOuNTAIN, section 3.2).

Different users, with different vocabularies and with different mental models will not only view their data differently, but also view differently the relationships between real entities within their worlds. This is encompassed by the domains of ontologies. The UK needs to explore the implications of upper ontologies as a mechanism for translation, not only between data schema and between vocabularies, but also as a translation route between different world models (RLAW, p. 42). Even without an upper ontology, the UK needs the capability to underpin data exchange and integration by developing an appropriate approach to develop new, to extend and adapt existing ontologies, and to create the means to integrate current schema and classifications (FOuNTAIN, section 3.2). Note specifically the need for ontological alignment between regulations and standards across to the data frameworks that will be used in the same space. Mismatches here will undermine the value of each. Temporal scales will matter as well as spatial scales and frameworks for combining and sharing data will need to cope with both 'fast' and 'slow' data sets and models (UIL b, section 3.2).

Doing this needs also a clear grasp of the decisions that are to be made by owners and managers of the assets (and by the managers of services that depend upon the assets) and hence an understanding of the data and information that will be needed. This implies the ability to create reference process models that can be used as tools to map the decisions, the data and how these vary across the life of the asset or the use of the service (FOuNTAIN, section 3.2) and (Enzer et al., 2019, Task 3.2).

The development of these capabilities will be an extension of systems for individual construction sites and for individual assets, such as those reported by Lee, Park, & Song (2018) and small scale demonstrators such as the Tombolo products produced by the Future Cities Catapult (2018). In

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[13] Examples include: Industry Foundation Class (IFC); Uniclass-2015; Construction Operations Building Information Exchange (COBie); CI/SfB; and City Geography Markup Language (CityGML) (FOuNTAIN).

the future, whole networks of built assets, infrastructure and services will potentially be managed in ways that will rely on structures, schema and tools. Below is a selection of the topic areas to which academic research could contribute.

Standards

Standardisation (G2), which will play a key role in the governance of these tools and their use, is highlighted in Tasks 3.2, 3.7 and 3.12 of the DFTG roadmap (Enzer et al., 2019). To take just one example of the importance of standards, robust standards for data exchange is highlighted as the greatest technical barrier to widespread uptake of immersive technologies (Vision, p. 22).

Discoverability

Widespread use of models is likely to result in an explosion in the volume and variety of data generated, and there will soon arise issues of how best to find and interrogate such data. Furthermore, one could envisage useful data sets of value to researchers and, again, discoverability will become a live issue. Therefore, the UK needs to develop capabilities to make the data and information discoverable, in ways that are accessible to query by a wide range of users, and to enable automation of such searches and queries.

In alternative modes of operation, tools surrounding models of assets and services might be tasked with delivering information in formats and under pre-defined protocols. The UK will need a capability in data and information discovery, query and delivery that will be met by the development of fit-for-purpose software (FOuNTAIN, section 5) which enables stakeholders:

- to query information repositories visually or using natural language,
- to explore information repositories based on current data models,
- to interrogate information repositories automatically using ontology-based tools, and
- to set information delivery schedules based on industry and project protocols.

In parallel with the frameworks that will allow both data sharing and the emergence of a market in tools that enable the agreed structures, processes and governance (for collection, storage, management, discovery, interrogation, sharing of data and information), organisations will need to establish their own processes and tools to gather and curate data and information and to manage its storage, maintenance and use. This capability will allow owners and operators to create and maintain a building model that will provide a single accurate source of up-to-date information which ‘creates a single source of truth’ (CAR, p. 32).

In summary, the underlying framework that will enable the secure and resilient sharing of data will be fundamental to linking together data sets and models. Such linkages will enable broader data sets, better models and hence the journey from insights to impact.

D3 Develop and manage federated and hierarchical models

The motivation for developing and managing models is well embedded in today's BIM practice and the extension to models of services and, indeed, of the business as a whole is discussed in the introduction to this section. The work to be done to underpin the capability is an extension of work already being done around BIM models and the sharing thereof.

Developing such models and their logical development, such as the digital twin, will be an expensive undertaking. Therefore, it is important that its commercial value is understood, and that it is coherently embedded with the governance, decision-making and organisational processes of its owners and users. Only in this way will digital twins and similar data modelling technologies deliver value and, importantly, contribute to wider understanding and better decisions (Wan et al., 2019).

Certainly creation, management and use of models has been given major impetus by the report of the National Infrastructure Commission in calling for digital twins of the UK's infrastructure and city assets (National Infrastructure Commission, 2017b). There is considerable work continuing in digital twins as the Digital Framework Task Group[14] maps out tools for interaction and interoperability, while CDBB's Digital Twin Hub[15] is a resource for organisations and researchers wishing to develop the topic. The DFTG's 'Gemini Principles' (Bolton et al., 2018) articulate the foundation principles for such models and their use.

Models also offer the ability to generate synthetic data about aspects of the asset that cannot be directly measured. So, for example, given a hypothetical wind speed and direction, a model could predict structural stresses. The tools for calculating unobservable states have been available for decades and applied in the aerospace sector for some time. The potential for use in the built environment is yet to be explored, but is an obvious extension of models of built assets and infrastructure, especially, of digital twins, for example in health monitoring and decay or damage prediction.

The data within the models of built assets will be essential to allow the use of immersive technologies; virtual and augmented reality and transfer between models (BIM in this case) and VR systems is under research (Du et al., 2018). Use cases for immersive technologies span the entire asset lifecycle including i) Client/Public Engagement, ii) Design Support, iii) Design Review, iv) Construction Support/Progress Monitoring, v) Operations and Management and vi) Training (Vision).

Organisations wishing to adopt models will need to note the significance of organisation aspects (D1.2) as well as the structures and schema (D2) to allow model federation and data interchange. Integrating models is a live topic of research with some exploring federated and distributed models, and considering the impact on organisational practices as well as the needs for integrating schemas and tools (Beach et al., 2017). There remains much to be done in the theory and practice of developing and successfully integrating models in these contexts

[14] http://www.cdbb.cam.ac.uk/DFTG
[15] http://www.cdbb.cam.ac.uk/DFTG/NDTHub

The underlying conceptual constructs embedded within models will need to match those embedded within the ontologies (see D2.2 for definition) that underpin the schema and the standards used. This is further emphasised when combining semantic information with model data. This is an area ripe for research.

The interfacing of models will need to be managed with reference to both the spatial and the temporal scales of the models. For example, how will the spatial interdependencies between sub-systems be modelled within the context of the building? And then how will the building's relationship to other landmarks be modelled within the context of, for example, geographic information systems? Temporal scale matters too (UIL b, section 3.2). How will models of 'fast' phenomena (say with models of lifts with time contents measured in milliseconds) be related to models of 'slow' phenomena (say, thermal changes within a building)? These issues have long been recognised (Batty, 2010) and work has been ongoing since, though much still remains to be done to demonstrate mature capabilities in specific topic areas.

The extension and integration of models of built assets with the services they support, and then perhaps on to models of the business itself, (the latter envisaged by (TH, p. 38f) is an open field with much research needed to enable such integrated modelling.

D4 Develop and manage data sets

There are distinctions to draw between legacy data sets and new data sets, with regards to data attributes such as security and quality. Despite the many factors and facets listed throughout this document, developing new data sets and their surrounding architectures from scratch is relatively simple when compared to the complexity of transforming the scattered, heterogenous and widely varied data that currently exists into an interoperable resource. Much research and many practical projects would be needed in order to develop this capability.

This section looks at capabilities underpinning the development and management of data sets, both new and old:

- Identify and mange for value (D4.1)
- Specify and manage data attributes (D4.2)

D4.1 Identify and manage for value

As discussed in the section on VALUE, there is much work underpinning the ability to gather data and extract value from it. It relies on having a clear understanding of desired outcomes, organisational, sectoral and national processes, frameworks and tools for deciding what data to procure and scoping out how it can be shared, and understanding the limitations and uncertainty of the data.

One of the main issues around the value of data that is not addressed elsewhere in this document is the value that comes from sharing it with a wider audience of stakeholders. A continuing debate surrounds the advantages of 'open' data, its value and the most appropriate definition of 'open' in any particular context. One of the chief barriers to good practice in this area is the notion that open or shared data somehow precludes competitiveness between researchers or businesses. Organisations 'might not engage in sharing because they fear a loss of control over their data when it is re-used by third parties. Furthermore, companies might simply not know (yet) that 'their' data can be useful for other players without harming their own business interests' (Richter & Slowinski, 2019). Still others see open data as an investment without sufficient return, or with high risk (Deloitte, 2017c).

However, the benefits of sharing data and information can certainly justify the investment. Organisations that begin by sharing data with customers and partners can develop stronger relationships based on trust, and unlock new value streams (Herschel, 2017). Sharing data in the infrastructure sector could release £15 billion in benefits per annum through greater efficiency, innovation and resilience (Deloitte, 2017c). The value proposition for individual organisations, especially regarding the differences between value creation and value capture, will be more nuanced and deserves continuing research and definition.

Box 4

Sharing data can also stimulate innovation and improve transparency. 'For instance, the Bank of England, as part of its "One Bank Research Agenda", has committed to "opening up to the public previously proprietary data sets in order to crowdsource solutions to challenging policy questions"'. (Günther et al., 2017)

The implications grow more complex as personal data enters the frame. A report by the UK government highlights mechanisms (for example data trusts) that could be used to maintain competitiveness while reaping the considerable benefits of sharing data. Data trusts rely on third parties to manage access to and use of data across political, geographic, organizational or sectoral boundaries (Hardinges, 2018). The ODI's exploration of data trusts suggests that, 'Cities or boroughs could use data trusts to decide how data that's collected by sensors in the built environment is used and shared to make cities easier to navigate for citizens' (Open Data Institute, 2019). With data trusts only one of many candidate ways forward, clearly there remains policy work to be done on data ownership and intellectual property.

Of course, the digital analysis of 'closed' or proprietary data can open up new avenues for value creation, as discussed in the section on value, through modelling a larger or more diverse body of data than was previously possible. This could deliver insights leading to new business or financial models, to better performance of built assets and services, or to new customer bases. Research in this area can develop the technology to capture value, as well as identify and evaluate demonstrators of value creation. It could also help unpack the interdependencies and levers that exist in between data attributes and outcomes.

D4.2 Specify and manage data attributes

The attributes of the data that feed into modelling and into decision-making will determine the quality of the outcome. The specification of required data and its management is already a recognised issue, enshrined in the guidance volume of 2019 BS EN ISO 19650 (UK BIM Alliance, 2019) and the evolution of both guidance and standards continues. Security, accessibility and discoverability are discussed elsewhere in this document and so the primary attribute dealt with here is data quality. Without robust quality assurance processes, data repositories have the potential to become 'data swamps' through, 'dumping raw data… without appropriate ownership or a clear view of business needs' (Brocchi et al., 2018). The 'garbage in, garbage out' cliché means that errors, gaps or other flaws in data will result in substandard models and, in turn, substandard decisions.

Quality as an attribute of data is fundamental to ensuring trust in digital systems. However, for sound commercial reasons, there are decisions and trade-offs to be made when defining, measuring and managing data attributes.

Data quality may mean different things to different stakeholders depending on their relationship to data. Haug (2016) presents five different views on what constitutes 'good' data:

- Transcendental: 'Good quality is un-definable; it is only recognized by experiencing it.'
- Product: 'Good quality is a function of the ingredients (inputs to the process).'
- User: 'Good quality is based on each user's needs and (perhaps unspoken) expectations.'
- Manufacturing: 'Good quality is based on conformance to specifications and process.'
- Value: 'Good quality is based on how much the customer is willing to pay for it.'

> ***Box 5***
>
> 'The common belief that problems with data quality usually stem from technology issues is mistaken. When one bank diagnosed its data quality, it found that only about 20-30% of issues were attributable to systems faults. The rest stemmed from human error, such as creating multiple different versions of the same data. Robust data governance is essential in improving data quality.' (Brocchi et al., 2018)

These definitions of quality are not necessarily mutually exclusive, and each gives a different perspective that is worth exploring in the context of digital built Britain. Others add 'diagnosticity' to this list (e.g. Ghasemaghaei & Calic, 2019), defining good quality on the ability of the data to lead to effective decisions.

Framework approaches to this have been developed (Woodall, Borek, & Parlikad, 2013) looking at different quality assessment techniques and identifying their potential contributions depending upon application. In some cases, the potential impact of information quality on organisational performance is uncertain, and hence risk-based approaches to defining quality requirements become appropriate (Borek et al., 2014).

An assessment of the state of the art in information quality management among asset-intensive organisation was performed by (Woodall et al., 2013), and reflects on the maturity models available and identifies critical success factors. Such work suggests a foundation for guidance in this domain.

Different stakeholders and contexts may require different data standards, and this should be enshrined in the organisational governance and in the choice of structures and protocols. This may be by reference to established standards (e.g. ISO 8000), government guidance (Government Statistical Service, 2019), existing organisational or sectoral guidance, or it may be created for the individual purpose. Various frameworks and case studies of common data environments enshrine data quality as a necessary attribute without defining it (e.g. National Infrastructure Commission, 2017; Mordue, 2018), while others go on to explore it in detail. For example, recent research explores the fundamental organisational needs for information and considers the boundaries between capital investment decisions, risk management and operational performance (Heaton, Parlikad, & Schooling, 2019).

Data ethics and cultural perceptions introduce a range of other attributes that need to be considered (Housing). Note that these perceptions and social norms of acceptable use evolve over time, sometimes quickly, while regulation follows in due course. The collection of large and personal data sets within the context of services and built assets will be an important topic about which there is new research to be done.

In the academic literature, discussions about data quality are accompanied by different technical solutions for assessing and managing it. There is no shortage of work in this area and innovation is rapid (Gap Analysis). Because of this, Karkouch et al. (2018) argue that data quality specifications should be developed separately from the technical solutions, a philosophy aligned with the guidance from current standards.

Users need also to be alert to mechanisms by which quality can be degraded and research is needed to classify potential issues, providing both guidance and solutions. For example, errors arising during acquisition could result from loss of network signal, degradation of sensors, environmental interference, vandalism, cyber-attack or data stream processing (Perez-Castillo et al., 2018). Processing, cleaning and anonymizing data can also introduce issues with accuracy, relevancy or descriptiveness of the data. This, too, is an area for further work.

Through-life data

Specific issues have been highlighted in the key capabilities of acquiring and updating the data for a built asset throughout its life. The ability to manage 'as-is reality capture' (CAR, section 4.3.1) and 'ongoing reality capture' (*ibid*., section 4.3.2) are two of the prime topics and they explore in detail the capabilities needed (B3). They note specifically that i) the conversion of point cloud data into useful model artefacts, ii) the addition of semantic information to augment data and models, and iii) automating these processes to make then economically viable are key capabilities needed now. Note also, that for legacy assets, extracting and monitoring information and data about hidden building services is a capability that would be of value to practitioners, but seems not to be a subject of much research yet (*ibid*., p. 91).

As well as collecting information and data, there is also the matter of maintaining a picture over time of the use and condition of the built asset. This data is also valuable, not only for the management of the asset but also for assessment of its operation and of the services that use the asset. Management and optimisation of energy and emissions performance, structural health, and lifecycle cost management are highlighted by as valuable capabilities (CAR). This data, of course, then becomes a foundation for the various models of the building (geometric, operational, predictive, etc.) and contributes to its value.

Managing data sets through life and, especially, as the asset is developed and reconfigured is a challenge, already encountered in the world of BIM, especially across collaborating organisations. The topic interacts with the ability to select and use appropriate common data environments and document management systems (Jager, 2018) which, themselves, will have a variety of organisational aspects to be considered in implementation. The functional requirements for Common Data Environments are set out by the UK Government BIM Working Group (Burgess & Tappenden, 2018). Developing the organisational capabilities to make best collaborative use of data environments will be important and current research explores the issues and suggests future directions (Shafiq & Lockley, 2017). It is clear that there is much still to be done.

CAR also highlights the potential for gathering information about the comfort and behaviour of users of the building (*ibid.*, p. 27, section 4.3.2). But note the myriad complications here about privacy and security, and hence the need to comply with both organisational and national governance frameworks.

In summary, the creation and management of secure, trusted data sets depends upon governance and process schema. The value of data is context-specific, dependent upon decision-makers' understanding of the uncertainty, security, quality, context and other attributes of that data relative to their purposes. Whether managing existing data from legacy built assets or creating new data about an asset through its lifecycle, these governance and process schema need to be created to navigate this complexity. Only then can data underpin better understanding, better decisions and better outcomes for stakeholders.

GOVERNANCE: Govern and manage, using appropriate systemic perspectives, tools and projects

The introduction below provides an overview of the **Governance** category of the Capability Framework for creating a digital built Britain.

Click here for an introduction to the **Capability Framework** as a whole, including links to all the categories involved.

Governance capabilities

Govern and manage digital built Britain and its projects

- Design and manage the regulation of digital built Britain (G1)
- Create and manage consistent standards (G2)
- Create and standardise new reference contract structures (G3)
- Understand how integrated infrastructure, assets and services should be built and managed (G4)
- Understand the potential and use of data and models in structured decision-making (G5)

Introduction

Everything that we do within the digital built Britain of the future will be governed by the laws of the land, its supporting legislation, regulations and standards. We need capabilities to choose the right regulatory regimes and to create standards that support rather than impede innovation. When creating regulations and standards we need to take account of the fact that data and information often span sector boundaries and that people and companies may need to share their data. A specific example, which highlights many key issues, is the automated checking of digital designs to make sure they comply with codes and standards. For this to work, regulations and standards need to be written in ways that machines can interpret and process.

This section highlights two special capability areas relating to regulation: those needed to digitalise the planning process and those required to explore and develop, if appropriate, a national database of key assets and infrastructure. These two areas provide examples of initiatives in which much research has already been done exploring the impact of data, information and models and which could act as flagships for the impact of digitalisation in the built environment.

As new business models emerge, and as services increasingly depend upon the data from built assets, so contractual obligations may extend right across the lifecycle, from construction and operation, to renewal and replacement of assets. If a data error causes a lift to malfunction in a city skyscraper, for example, we will need the frameworks to explore liability.

Much has already been achieved. Great success has been attributed to legislative action such as the mandating of Building Information Modelling (BIM). The role of standards is also recognised as critical. In these areas, research can underpin pragmatic developments in tools for immediate use.

We need the capabilities to define, design and manage the complex projects that will create and maintain digital built Britain. Across the UK there are many examples of tightly integrated systems, involving infrastructure, transport, energy and communications, which are managed by different groups, and where a shortfall in service performance in one will damage them all. We need to develop deep insights and skills in building and managing these complex systems. The mega-projects by which these systems are created, and the management of the critical infrastructure involved, often exists at the point where legislation, planning, complex contracts and systemic effects intersect. Much research is currently being done in this area and there is considerable momentum upon which new capability can be built and disseminated to support better understanding and decision-making.

The greater availability of information for those involved in making complex decisions places a premium on the robustness and transparency with which problems are framed, options are explored and decisions made. Digitalisation offers ever more powerful tools to support this. We need to build the capabilities to use these tools, so that we can improve decision-making and communicate more effectively.

G1 Design and manage the regulation of digital built Britain

While work continues in this whole area of governance there has not yet been a review for the purposes of digital built Britain. There are many candidate strands. For example, what is the preferred perspective on the questions that regulation raises? Obviously digital built Britain can be seen as an evolving socio-technical system (STS) and thus a STS perspective may be appropriate (Meacham & van Straalen, 2018). As the services dimension becomes more important, so arises the question how best to regulate these, explored further in current work (Hiteva et al., 2018). Standards development has continued as BIM is rolled out. The tighter integration of services and of assets, accompanied by the convergence of different sectors will raise new challenges in creating coherent and consistent standards.

This capability reflects upon a fundamental question of the approach to be taken to governance, before moving on to the issues of regulating a fast-changing world. This section then considers two special cases; planning and national databases. The underpinning capabilities discussed in this section are:

- Explore options and make specific decisions about the nature of governance most appropriate to the situation (G1.1)
- Design and manage the regulation of digital built Britain (G1.2)

And then two special cases:

- Develop the planning regime and mechanisms in light of digitalisation (G1.3)
- Establish the potential benefits and disadvantages of centralised monitoring, data collection and management of UK national assets and specify accordingly (G1.4)

G1.1 Explore options and make specific decisions about the nature of governance most appropriate to the situation

Digitalisation has already demonstrated its capacity to have a massive impact on commerce, on productivity, on social cohesion and on the happiness of people in the UK. But it is not at all clear what might be the balance between opportunity and threat and the way forward. Tim Berners-Lee created headlines with his concerns, expressed on the 30th anniversary of his invention, about the way the web has evolved (Berners-Lee & Cellan-Jones, 2019).

But is the solution to be the imposition of centrally governed regulation? Should the favoured approach be one of self-governance, such as that offered by the W3C consortium[68] and its standards creation process[69], and the activities of the Internet Engineering Task Force[70]? Or should there be a decision to not intervene, making that choice – and its trade-offs – explicit? What might be the better approach when the interests of the commercial organisations working with data and information across the built environment begin to conflict with the interests of the people working and living within digital built Britain?

Previous work in this area indicates the complexity of the domain and the myriad considerations, especially with regard to infrastructure. Marsh & Ersoy (2016) explore the schools of thought in governance, its history with regard to infrastructure in the UK and its purpose, before going on to propose new approaches. Importantly, they highlight the complex interplay between 'broader questions of purpose, value and benefit', in the context of systems thinking and infrastructure interdependencies, and matters of design, delivery and funding, while addressing trade-offs between intangible benefits and economic assessment. Governance has a role to play in managing these debates and trade-offs.

Always there is the interplay between the support of innovation and the protection of the public (Abbot, 2012). As flagged up by Urban Innovation Lab, while devolution of transport powers to English local authorities will enable them to have more control over local investments, it does run the risk of losing an integrated approach and, by implication, a series of local optimisation exercises at the expense of better overall performance (UIL b, p. 8).

Flyverbom (2016) introduces new ways of thinking about governance, and especially about information control and visibility. The thinking about transparency plays across into other aspects

[68] http://www.w3.org/
[69] http://www.w3.org/2019/Process-20190301/
[70] https://www.ietf.org/about/

such as discoverability and security. Although his focus is on governance of the internet, much of his proposed research agenda applies here, especially in the context of the built environment as a socio-technical system and the perspective opens up new ways of thinking about the implications of digital built Britain.

The UK needs to develop the capability to choose, for each situation, its governance philosophy, address the questions posed above and to be able to do so repeatedly, effectively and efficiently as digitalisation proceeds. Failing to identify decision points – and then make the decision – runs the risk of reactive regulation after the event and, potentially, too late. The security implications within a more integrated and digitally enabled world multiplies the risk (see D1.4 for a discussion of data security).

G1.2 Design and manage the regulation of digital built Britain

All stakeholders and participants in digital built Britain will be subject to a set of 'rules of the game' which will, in practice, arise from legislation and regulation, much of it targeted at specific industries but nonetheless applicable; from standards and their accompanying guidance, both national and international; from contractual frameworks designed to streamline large collaborations; and from myriad perceptions of the customs and norms from doing business. The response of stakeholders will depend not only upon their specific objectives and strategies, but also upon their resources, and all coloured by their interpretation of the 'rules of the game'. Digitalisation, increasing integration of services and built assets and the convergence of sectors will mean that this complex landscape will need careful navigation by all involved. New technologies will guarantee that the landscape continues to change.

Central to this will be the ability to assess the implications of policy changes, of regulation and standards changes and how they will play out over time (SW – Social Constructs). This is difficult because each new initiative will be part of a wider mesh of interacting legislation and standards. Evolution over time will be important, both as subsequent legislation, standards and external drivers impinge, but also as actors respond to the new legislative landscape. Regulators will need to be alert to how new regulation about a digital world might impact legacy regulation (identified in consultation workshops[71]) and must also be alert to how digitalisation might change the ground rules within a sector. This is exemplified by OFGEM's need to work with smart meters and super-grids (TH, p. 43).

Regulations applied elsewhere will impinge as sectors converge (for example as transport and energy converge (UIL b, section 1.2), and so there will need to be coordination between the regulators. Initiatives such as the UK Regulators' Network[72] and the LSE Regulators Forum[73] are useful co-ordinating mechanisms. Imperatives here may include a focus on critical infrastructure or assets, especially as, in future decades, they become increasingly integrated and, maybe,

[71] Identified as an issue – see SW – Social Constructs
[72] http://www.ukrn.org.uk
[73] http://www.lse.ac.uk/accounting/carr/research/regulators-forum

interdependent. The National Infrastructure Commission called for greater regulatory activity to drive data sharing and the extraction of value, both from infrastructure and geospatial data (National Infrastructure Commission, 2017b). There needs also to be an explicit interface to the Digital Framework Task Group, who recognise this interface as Task 2.7 in their roadmap (Enzer et al., 2019).

As digital built Britain develops the services which are embedded in and delivered though built assets, so the design and management of regulation will need to recognise this and explicitly cater for the issues across the interface, a point raised in CDBB consultation (SW – Social Constructs).

Concerns over ownership of data and of intellectual property in data sets and models is emerging as a barrier to the wider adoption of digital tools (CAR, p. 26), suggesting that this be a topic for specific attention, with some suggesting government policy intervention (Linden, Almond, & Patterson, 2018). Ownership and property issues therefore become a key capability to enable the adoption of asset and service models and the benefits that flow from their use.

The final, and vital, aspect of this capability is to embed, from the very beginning, the capability of encompassing automated compliance checking. The D-COM network (Digitisation of Requirements, Regulations and Compliance Checking Processes in the Built Environment), funded by CDBB, have created their 2025 roadmap for the complete overhaul of the system from today to a world of automated compliance checking (D-COM). The credibility of their approach is supported by the results of their survey from which they report that, 'Overwhelmingly respondents indicated that automation was possible, with the vast majority of respondents believing some level (partial of automation with human oversight) are achievable by 2025' (*ibid*., p. 37). They provide a useful graphical illustration of the scope of their landscape (*ibid*., figure 4) that shows the interplay of use cases, purpose and example regulations across the asset-lifecycle.

D-COM go on to map out the current and future operating models envisaged and describe the engagement activities and prototyping proposed to demonstrate the benefits and implications. They fully recognise two fundamentally different approaches to developing capabilities: those where research, new knowledge and new tools may be needed, and those where it is a matter of mobilising market forces and the opinion of influential stakeholders. This distinction informs their plans. Usefully, they survey the current state of the art with respect to tools, their use and adoption (*ibid*., table 3)

D-COM identify the important elements of their roadmap (both capabilities and tasks to be done), categorised as technical, commercial and political, together with the co-ordinating actions and influences that need to be brought to bear. From their work, the following broad capabilities can be drawn:

- The ability to define benefit, and build and follow through on the investment cases and newly enabled business models.
- The ability to structure and write regulations in ways that make them amenable to use in automated checking. To enable this there will need to be alignment between the mental models, the ontologies and the schemas used by authors of regulations and designers (Note the connection to (see DATA).

- The ability to design the processes to make best use of the automation opportunities, respecting the boundaries of capability and creating appropriate safety nets for uncertainty, and for feedback. Mapping of such processes might be usefully linked to the process mapping envisaged in the work of the DFTG under Task 3.2 (Enzer et al., 2019).
- The ability to manage asset and associated data with full provenance and quality checking, and the ability to work within consistent data models, schema and tools (D2).
- Explore and adopt generative designs that will align with regulations and guidance, entailing research into generative design tools.
- Looking to the through-life aspects, the ability to create continuous checking regimes with the supporting acquisition and management of data and information.

The coordinating actions that D-COM suggest are all directed towards creating the aligned political will among policymakers, regulators and respondents to pursue the agenda, accompanied by the cultural changes that will be necessary to support the adoption and assimilation of the new capabilities. Additionally, D-COM note the importance of security (*ibid*., p. 39) in all aspects of digitising the built environment and the need for development of technical competence among all involved practitioners. Table 6 of their report details the rationale, key enabling factors, barriers and suggested research needs for the capabilities they have identified.

All that D-COM proposes is predicated on sound data sets and comprehensive models that can be checked against the relevant regulations and standards. To extract the benefits promised by the D-COM proposition, the models and their management must to be developed in line with a philosophy of automated compliance checking.

As well as research to inform and underpin this technology, developing the capability to design and manage complex and interacting legislation, regulation and standards might also be an opportunity for a pilot or demonstrator (SW – Social Constructs), which, with a focused scope, may offer a quick win to enrol support.

G1.3 Develop the planning regime and mechanisms in the light of digitalisation

The planning process is so central to the effectiveness and efficiency of the permissioning that surrounds the built environment that it deserves specific attention. The Housing Network produced a position paper on the topic (Housing 4) to which the reader is referred for a discussion of the issues in the context of digital built Britain.

The topic is already the subject of considerable attention, debate (Future Cities Catapult, 2016; 2018; n.d.; Pringle, 2018) and experimentation (King, 2017), covering topics as diverse as creating and accessing local data sets, and the use of 3D visualisation in support of planning new developments (Miller et al., 2016). The Vision Network confirm the value of immersive technologies in public engagement, particularly helping the public to visualise the visual impact of proposed new developments (Vision). Other research has developed a framework which describes the stakeholders' involvement against dimensions of 'smartness' and relates the evolution of a project through planning within the context of a smart city (Axelsson, 2018). Yet further evolution is envisaged in the continued development of Planning Support systems for smart cities (Pettit et al., 2018).

There needs to be care in the development of planning systems that respond to the overarching metrics established to assess the performance of digital built Britain. UIL (UIL b, p. 34) highlight Gibberd's work showing dissociation between the planning systems used and the sustainability indicator frameworks such as ISO 37120:2014 (Gibberd, 2017). The speed of decision-making itself has an impact on the cost, politics and decision quality of planning. With the emphasis placed on speed of project delivery, the planning sector favours larger players with more resources, meaning that research is needed to unpack the consequences of time pressures and deadlines on decisions in the context of the built environment (Raco, Durrant, & Livingstone, 2018).

However, managed well, developing the planning system could have wider implications and might be a useful case study for many of the governance and interdependency issues to be addressed in digital built Britain. 'Digitisation could enable different policy goals to be tackled simultaneously through a better and more efficient understanding of their interdependency - such as housing and health, transport and local economy, existing infrastructure and industrial heritage etc.' (Housing 4)

Digitising the planning system may allow a better risk assessment, for instance by making risk-related data available for all planning stakeholders. This is the objective of digital platforms such as Land Insight which provides information on environmental constraints such as floods as well as planning decisions on a single map-based platform (Future Cities Catapult, 2016a). See also the discussion of managing flooding risk in section C3.

The Housing Network (Housing 4) lay out the context and the problems, and identify current innovations and opportunities, illustrated with case studies. They conclude that the primary needs are the abilities to:

- Discern and articulate the benefits (see V1)
- Understand the potential advantages to be gained from wider use of digital tools
- Set priorities for revision of the parts of the planning process
- Determine the best locus for governance and regulation – local or national co-ordination
- Target and pursue the development and adoption of tools

They note the significance of capabilities in modelling and understanding complex integrated systems (G4), assessed as a whole rather than in parts. NESTA[74] go further and, in addition to a commentary on the current issues and future opportunities, propose a prototyped open-source and 'hacked' demonstrator. They also signpost examples of apps in use (Parvin, 2016).

Cowie (2017) identifies standards and standardisation as a key element of freeing up the humans to focus on the most complex areas where they can add the most value. D-COM confirm the potential, but note the need for planning policies to be designed and articulated in ways that cater for future development and in the context of agreed and structured data models (D-COM).

[74] http://www.nesta.org.uk/feature/civic-exchange/open-planning/

This specific area, then, is ripe for focused development of new capabilities and could provide insights across the full gamut of topics in regulation, standards and the potential for digitalisation to improve the planning and design of digital built Britain.

G1.4 Establish the potential benefits and disadvantages of centralised monitoring, data collection and management of UK national assets and specify accordingly

The discussions around capabilities often prompted suggestions for the creation of national data sets about buildings and infrastructure. Turner Harris formalized this into a suggestion for the creation and use of a 'National database and knowledge resources for major asset classes across the UK', targeted specifically on providing controlled visibility and access to digital asset information to support national planning and emergency response (TH, p. 44). Managed well, it can be seen as a foundation for a knowledge base, for research and for more co-ordinated decision-making. CAR proposed a similar database to draw together existing building data into national datasets about building stocks and their condition (CAR, p. 12), again as a resource for policy creation and for more integrated prioritisation of management in both the public and private sectors, and for benchmarking environmental and sustainability performance (CAR, p. 23). Other purposes proposed include the management of building stock and, depending upon content, exploring the project performance as assets and infrastructure are created. Such projects may be seen as tools for comparison and learning about good analysis and decision-making (Uncertainty, section 1.3). Such data sets depend critically upon the ability to specify and maintain robust systems and structures for sharing data between organisations and over many years[75].

Indeed this idea of a central data set and model is at the core of the National Infrastructure Commission (NIC) report 'Data for the Public Good' (National Infrastructure Commission, 2017b). This NIC report initiated the development of the Digital Framework Task Group (Enzer et al., 2019), whose efforts will be a major contribution to some of the capabilities sought here.

Such tools could be augmented by the network of urban observatories under the auspices of UKCRIC[76] and bodies such as the Urban Big Data Centre[77]. The Future of Cities Project's Lead Expert Group (Foresight, 2016) called for longitudinal data sets to allow evaluation of interventions, especially with respect to the social impacts and implications. Furthermore, the DAFNI project embodies the collection and use of infrastructure data.[78]

But there are, of course, concerns about sharing data both for commercial reasons and for the risks to security of critical infrastructure (CAR, p. 28). Linden et al. (2018) highlight the significance of managing the ownership and access to the datasets created, important for their likely criticality.

[75] Capabilities highlighted by CAR (2019), Turner Harris (2019) and FOuNTAIN (2019)
[76] http://www.urbanobservatory.ac.uk/explore/ukcric
[77] http://www.ubdc.ac.uk/
[78] http://www.dafni.ac.uk/

Developing the capabilities of a national digital twin is the domain of the Digital Twin Hub[79], while governance of digital twins is being researched under current CDBB-supported research (Nochta, 2019). As these projects develop, so the imperative, the content and the context for such capabilities will become clearer.

G2 Create and manage standards to underpin digital built Britain

The sheer scope of the standards landscape relevant to digital built Britain is immense. There are over 11,000 *de jure* standards that are in scope, and an anticipated similar number of *de facto* standards within sectoral groups[80]. However, the services domain, which is the vehicle by which benefits accrue to the citizens of digital built Britain, is the least served by existing standards. Furthermore, most standards describe how things are to be realised and the activities might be structured, but there is little to define how outcomes are to be achieved or measured, especially in the services space.

Standards and their accompanying guidance have played a fundamental role in the uptake and dissemination of BIM in this sector and in digitalisation across many sectors. They have also been a fundamental part of the smart city debate (Heaton & Parlikad, 2019). Certainly, the combination of well-targeted guidance, alongside standards is seen as critical by experts canvassed within this work (RALW, p. 27). Each of the sectors has their own information and standards infrastructure and domain expertise, especially about legacy systems will need to be brought together as sectors converge. Co-ordination will be essential.

Standards will have a role to play in so many aspects of the asset models: their creation in forms that can be shared and disseminated, their management in ways that enshrine and manage security and privacy, and the interoperability of the software and data products and services that make up the virtual infrastructure.

It is important to continue embedding the use of current standards and the planning of appropriate extensions of portfolios such as the ISO 19650 and ISO 8000 series. Such extensions will need to recognise the tighter interrelationships with services that will be part of digital built Britain, along with the increasing integration between different economic and social infrastructure, between systems and between organisations as sectors converge. Roadmaps for the evolution of such standards to enable integration and convergence would help alignment among the many stakeholders. This will become especially pressing with the increasing integration of services and assets (UIL 5). Such roadmaps have been developed in the past by convening organisations such as buildingSMART.

The convergence of sectors, together with their industry-specific standards is an issue of specific concern that will need to be addressed to enable the full benefits of standardisation and of

[79] http://www.cdbb.cam.ac.uk/DFTG/NDTHub

[80] We refer the reader to the set of reports by UIL (UIL 1-6) for a detailed exploration of the standards landscape and key issues.

innovation imported from other sectors. The creation and use of meta-standards provide a promising way forward here and is described in detail by UIL (UIL 5).

Standards will underpin the exchange of information throughout the real asset's lifecycle and creating and adopting such interface and exchange standards is key to better through-life management (CAR, p. 22). This will become yet more important as sensors based on Internet of Things messaging standards need to interface to the models of the assets (Dave et al., 2018).

Other key topics for development include:

- The creation of an architectural framework that is clear to follow, and a system architecture to show relationships and to hold digitised requirements, regulations and standards, with layers of checklist, rules-based algorithms and roles and responsibilities (D-COM).
- The design of standards and their implementing regulations in support of automated compliance checking, including standards clauses that are digitised and used under protocols that allow the clauses to be accessible digitally (D-COM).
- The development and use of standards related to data exchange. The FOuNTAIN Network specifically recommend the development of the capability to establish the appropriate scope, priorities and pace of standardisation, at industry, project and organisation levels for data exchange. However, they also caution for care in selecting the balance between standardisation and flexibility and hence for care in scope and targeting (FOuNTAIN, p. 7).
- The development and application of standards for the use of predictive modelling and the use of data.

Standards are also seen as a key enabler of new technologies and their spread across the sector. The Vision Network finds that a lack of standards is a limiting factor in several of the use cases for immersive technologies (Vision, section 4.1.1).

The gauging of information management maturity, as part of existing standards or new standards, has also been suggested (FOuNTAIN, p. 6). This could provide a framework within which companies can develop their integrated use of data, information and models as decision-support tools (see DATA).

There is work still to be done exploring standards that pertain to the interface between services and the built environment (UIL b, section 3.2).

The development of this capability and the ensuing development of standards need to be conducted by standards bodies working in collaboration with industry groups. Only in this way can there be the best combination of targeting, of development, of testing, and of dissemination of the standards and the insights embodied in the guidance (UIL 1). There is a strong international element in the development of successful standards and, as sectors and technologies converge, considerable cross-sectoral collaboration. The early involvement of developers of new and emerging technologies is also essential if new technologies are to be adopted effectively.

Examples of different relevant standards bodies and processes are described in (UIL 1) and a mapping of standards between and across sectors can be found in (UIL 2).

Note specifically the need for ontological alignment between regulations and standards across to the data frameworks (D2) that will be used in the same space. Mismatches here will undermine the value of each.

The accessibility of standards, their authority and their combination of guidance and requirements makes them a powerful force in the creation of digital built Britain. This is an important area in which extensive and ongoing work must continue.

G3 Create, standardise and roll-out new reference contract structures which will support the realisation of digital built Britain

Digitalisation alone will have a huge impact on the relationships between actors in digital built Britain. The sections on SERVICES, on the BUILT ENVIRONMENT and on DATA discuss the needs for new business models, for new definitions of outputs, responsibilities and liabilities, across potentially new interfaces and through supply chains and ecosystems that are likely to be very different. All of these will be affected by the governance framework of the prevailing contracts. The Digital Framework Task Group recognise this within their roadmap as Task 4.9, 'Identify and manage commercial enablers' (Enzer et al., 2019). The convergence of sectors will be another driver. Against this backdrop then, the evolution of contracts will be needed which reflect the realities of new business models, together with the roles and responsibilities for information creation, management and maintenance (including security and access).

Work is underway in these topics, for example considering BIM, its evolution and its impact on contracts, noting the need for reliance on BIM software (Mosey et al., 2016). Such efforts suggest that continued development of contracts in the context of increasing use of models as a foundation for collaborative work is a promising direction. Other work explores the potential for reduction in disputes from digitalisation and, in particular, the shared data and the explicit exploration of assumptions by the parties involved. Such aspects will be a fundamental part of the creation and management of digital built Britain, and the UK should develop the capability to combine contracts and models in the most constructive way possible.

Exploration of contract theory has been suggested (Phase 1 Report, p. 33), including relational contracting, enterprise contracting and the interaction between the choice of commercial models and the contracts to implement them. Outcome-based contracts are attractive in principle, but challenges remain, and the different sources and character of risks need to be addressed (UIL a, p. 52 and section 3.3.2). In the context of coupled assets and services, any failure in capability distributes risk to other partners. The potential impact on conventional business models is immense and hence the capability to develop such contracts must be matched by an equivalent capability in business model development.

Framework contracts are a core part of the sector, and standardised forms support rapid engagement among experienced partners. It is important to understand whether and how digitalisation might affect these factors and so address them. Major new options are emerging, for example the Framework Alliance Contract, FAC-1 (Mosey, 2019, p. 1), and these provide a promising foundation.

Although there is enthusiasm for the contributions from new digital technologies, Blockchain chief among them (Lamb, 2018a), there should also be pause for thought to explore some of the downsides (Sklaroff, 2018), reflecting on the realities of human linguistic ambiguity and enforcement discretion in contract creation and management in the context of long commercial relationships. A study of the application of blockchain to the built environment highlights opportunities and challenges in the political, social and technological dimensions (Li, Greenwood, & Kassem, 2018). The Cloud is another technology of possible application in governance, and Alreshidi, Mourshed, & Rezgui (2017) propose a framework for cloud-based BIM project governance.

Through-life management of data is an issue requiring specific contracting. Renovation and refurbishment are domains in which further attention is needed around matters of contracts, licensing and intellectual property (Ilter & Ergen, 2015). Working practices will evolve, and with them the need to define, with the right mix of flexibility and robustness, the characterisation of data and information, and the associated responsibilities and liabilities in ways that will underpin effective contracting (RALW, p. 28). This topic will be closely linked with the capabilities discussed in the specification of data attributes and management (see also section D4). For example, using today's conventional contracting boundaries impedes the opportunities for wider data sharing amidst concerns about risk management and liability (UIL b, section 3.3.6 and TH, p. 15).

Another aspect of contracts lies in the matter of risk management and the enabling tools. Digitalisation will change the landscape, both to reduce and to increase risk in different areas for different actors. Examples include project and programme management and insurance services, which could be transformed by the integrated use of BIM and other models, especially in relating capital and operational expenditures with the uncertainties of time (Uncertainty, section 2.8). This too needs to be understood so that risk management, so much a part of the sector, can continue within a clear contractual framework underpinned by competent modelling. This is explored by Turner Harris (TH, p. 32).

Modelling tools will be of value here, especially models of revenues and risks associated with the complex interplay of services and built assets, and this is discussed further in DATA. This complex interplay will be at the core of value networks, and there may be other legal implications to be explored so that principles are established to underpin the inevitable convergence of activities and interests (UIL a, section 7).

As technology changes, so does the need for contract structures and language that reflect the relationships between stakeholders, assets and data. Opportunities are arising to manage compliance and contracting digitally, but will be accompanied by new issues to be explored. This is a rich area for continuing research, building on recent developments[81] and one where case studies offer opportunities to explore value and future directions.

[81] For example, http://allianceforms.co.uk/about-fac-1/

G4 Understand, predict and manage for the integration and interaction of infrastructure, built assets and services

Digital built Britain will be characterised by complexity, in part driven by the intrinsic nature of the sectors that will converge - for example transport, utilities, communications and infrastructure - and in part driven by the drive for tighter integration in pursuit of higher performance and 'more joined up thinking'. This being the case, it is imperative that digital built Britain has access to the thinking and the tools to engage effectively with this complexity and integration. Digitalisation will have a key role to play, developing data sets, models and decision-support tools at many different scales and enabling deeper understanding, better decisions, better projects and better outcomes.

Other sections of this document stress the importance of understanding the linkages between the drivers across the many sectors that will contribute to digital built Britain. UIL highlight this as an issue (UIL a, section 7), both generally and in the sectors they explore. Furthermore, there will be many external drivers (see CONTEXT) that will affect its evolution. The capabilities that will underpin the understanding of those linkages are discussed here.

EPSRC has a research area in complexity science[82] which is relevant here, identifying outcomes such as ensuring a reliable infrastructure which underpins the UK economy, achieving energy security and efficiency, building new tools to adapt to and mitigate climate change, achieve transformational development and use of the Internet of Things and delivering intelligent technologies and systems.

Modelling of all kinds will be essential and the UK will need to develop the skills to define the models needed, learn how and when to use them, and how to work with the data and information involved – both going into the models and coming out. Ouyang (2014) surveyed the modelling approaches used to explore critical infrastructure interdependencies, flagging up the variety of approaches adopted for different purposes, especially in interfacing systems issues and economic modelling, and also identified candidate directions for future work.

This document touches on digital twins (D3) as a special case, but they too are an instance of the modelling capabilities that will be needed. The ability to link between the data and the models (especially when the models are federated) will be vital. Indeed, this entire capability is predicated on the ability to build and maintain, share and use federated models different temporal and spatial scales.

Considerable work is ongoing today. The vital importance of a strategic approach to planning developments of critical and coupled infrastructure is, for example, explored in depth by Hall et al. (2017) in their interdependency framework and their 'system of system' modelling in support of the National Needs Assessment (Atkins, ICE, & ITRC, n.d.).

Further examples of modelling can be drawn from a very wide range of activity, for instance urban models used to explore options in land use and travel demand (Hagen-Zanker & Jin, 2013), and interactions between benefits and disadvantages such as travel and emissions, linked to policy

[82] http://epsrc.ukri.org/research/ourportfolio/researchareas/complexity/

options (Grote et al., 2016). Carhart et al. (2018) propose systems approaches which suggest how collaboration and project governance can be undertaken to maximise value. The application of 'options thinking' offers ways to explore new avenues of infrastructure integration (Martani et al., 2016). There are several very active centres, for example the Infrastructure Transitions Research Consortium[83] and the Data and Analytics Facility for National Infrastructure (DAFNI),[84] Imperial College's Centre for Systems Engineering and Innovation[85], UCL's Urban Innovation and Infrastructure activities[86], and collaborations such as the Turing Institute's 'Optimising Flow within mobility systems with AI'[87]. Research roadmaps from such groups set out, for example, proposals for next generation tools to visualize and understand civil infrastructure as a complex product system (Whyte, 2016), and many conference series exist to bring academics and practitioners together[88].

CDBB's workshops (SW – Systems) and commissioned research confirm the importance of models, tools and their use and, especially the need to understand topics such as:

- The implications of scale and interaction effects between systems of different spatial scale (UIL b, section 3.2)
- The implications that will arise as new systems are integrated with legacy systems
- The consequences of integrating legacy systems that were not designed with integration in mind
- Emergent properties such as security, vulnerability and resilience
- The interactions between current, new and different supply chains of businesses and hence the impact on sector dynamics (RALW, p. 29)
- How to discern new constraints, requirements and opportunities as we pursue ever-tighter integration

To date, much of the modelling has been largely of and about 'hard systems' and 'hard science'. A direction that may deserve further attention is the integration of social science thinking and models into the tools to be used to predict and manage the dynamics of digital built Britain. An example of such work is Garcia-Diaz & Olaya (2017).

The interacting sectoral players will constitute a 'system of systems', in the sense that, for many purposes there will not be a single co-ordinating body but instead the managerial and operating systems will be independent (SEBoK contributors, 2019). This thinking has been applied to infrastructure systems specifically (Hall, 2016b), the engineering of such systems (Nielsen et al., 2015), and vulnerability assessment (Pant, Thacker, & Hall, 2017). Such thinking should be extended and disseminated to underpin this capability.

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[83] http://www.itrc.org.uk
[84] http://www.dafni.ac.uk/
[85] http://www.imperial.ac.uk/systems-engineering-innovation
[86] http://www.ucl.ac.uk/steapp/research/urban-innovation-and-infrastructure
[87] http://www.turing.ac.uk/research/research-programmes/artificial-intelligence-ai/programme-articles/optimising-flow-within-mobility-systems-ai
[88] For example, the International Symposia for Next Generation Infrastructure (http://isngi.org/) and Applied Urban Modelling (http://www.martincentre.arct.cam.ac.uk/conferences/AUM)

Particular attention should be paid to thinking through, and modelling, phenomena of different spatial and temporal scales. For example, how might climate change models be best coupled into decision-support systems for shorter term strategies and operational management? Indeed, many different coupling mechanisms need attention. For example, do we fully understand the coupling and the interdependency that arises as we design the data systems themselves and the representations that they give us (Sayed et al., 2015)? And can we evaluate the benefits that arise from integrated systems of utilities and transport networks and find appropriate management strategies (Kalyviotis et al., 2018)?

Another domain in which integrated modelling holds great promise for progress is in planning and managing for resilience (Cerè, Rezgui, & Zhao, 2017). Early UK Government work from 2012, looking at infrastructure and resilience (Guthrie & Konaris, 2012) graphically illustrated the nature and significance of interconnectedness of critical infrastructure, identified risks and difficulties and showed overall strategies. They made recommendations for several sectors and for both government and the professions, emphasising the importance of systems thinking, good data and modelling. A recent review undertaken for the National Infrastructure Commission (UCL & Arup, 2017) makes recommendations for approaches and toolkits to address resilience, while others are exploring appropriate metrics (Pant et al., 2017). In 2018, the Treasury commissioned a report for a new study into resilience (Hammond, 2018) to be published in 2020.

Earlier work in the USA (McAllister, 2013) developed a research roadmap to underpin guidelines and standards in support of resilience and disaster management. They point out the dependence of resilient performance of built assets upon the then prevailing standards and codes and go on to discuss the considerable interplay between standards across sectors including power, transport, water and wastewater, together with those applicable to the built environment. Cerè et al (2017), in addition to suggesting frameworks to consider the myriad resilience issues, highlight the positive effects that arise as resilience is addressed not as a static attribute, but as an evolving processes and the benefits that arise as a diverse community of stakeholders build better working interrelationships on the back of collaborative efforts to address resilience.

Resilience is also of concern among the organisations in the commercial sector, for example in insurance. Alliances are exploring the issues and the options for action across many sectors and to build a better overall appreciation of the emerging issues[89]. Yet others are exploring frameworks to maximise the potential for integrated and multidisciplinary exploration of this space (Carhart & Rosenberg, 2016; Rosenberg et al., 2014). A topic in its own right, this will underpin this very important capability and deserves specific attention.

Digital built Britain will continue the move towards increased integration. The research around the mitigation and management of natural disasters notes increased integration of increasingly complex systems as one reason for the increased magnitude of impact of such events (Etkin, 1999). Furthermore, risk transference, when mitigation strategies for lower impact / higher frequency events actually increase the impact of rarer events, is one example of the non-linearities that need to be incorporated into the thinking and the modelling of integrated systems (*ibid.*). Bringing

[89] http://www.resilienceshift.org/

together streams of work in complex systems modelling, in complex project development and in disaster risk management may give rise to useful synergies as the UK build capabilities in all these areas.

As integration within and between services and built assets increases, alongside our dependence on automation, the greater our confidence in those systems of systems will need to be. The understanding and insights from work in this area can provide widely disseminated guidance for all those involved in development and management as each new node of connection and mechanism of interdependency is added to digital built Britain.

G5 Embrace data and models effectively in structured decision-making

In a world of increasing complexity and integration there will be a premium on good decision-making that fully accounts for the inevitable uncertainties from myriad sources. A key question here is to explicitly scope out and decide how much analysis and investigation should underpin decisions. Large projects will continue to dominate the headlines, and this will place a premium on communicating, often with constituencies that are ferociously partisan, the multiple considerations, the decision itself and the unfolding project progress. Doing so in a way that is fair to all concerned is a capability that will be important – and hard to build and maintain. It relies on the dependent capabilities described below:

- Scope and design modelling and analysis support and processes for major decisions (G5.1)
- Discern, measure and communicate outcomes in major digital built Britain projects (G5.2)

G5.1 Scope and design modelling and analysis support and processes for major decisions

The Uncertainty Network carefully considered many aspects around improved decision-making, highlighting several key capabilities to be developed. A starting point is a characterisation of the decision-making environment, to ensure that the decision and the underpinning analysis are aligned to purpose. This would be helped by the creation of a taxonomy of the decisions involved in projects (Uncertainty, section 1.1) in order to make future research more immediately accessible to decision-makers and more immediately comparable across the research community.

Decisions in this space typically have massive implications and consequences. They are usually characterised by uncertainty, and, in the face of increased analysis and modelling, it is vital that uncertainty be visualised and characterised throughout the data management and modelling phases, within the decision-making itself and communicated effectively when the decision is made (Uncertainty, sections 1.1 and 2.2). This will become even more important as models are federated and as uncertainty propagates though the models and the associated analysis. Tracking the provenance of models and data is vital and a large research domain it its own right, characterised by several surveys and reviews (see, for example: Pérez, Rubio, & Sáenz-Adán, 2018; Ragan, Endert, Sanyal, & Chen, 2016; Simmhan, Plale, & Gannon, 2019). A W3C working group has developed a model for tracking provenance across web-supported data (Groth & Moreau, 2013), while others suggest ways to track provenance can be through sense-making analytics (Xu et al., 2015). This would also relate across to other capabilities VALUE and SERVICES, where it is important to surface mental models. Certainly, this is a large topic that would need careful structuring, especially if it encompasses the management of interlinked models.

Concerns are being raised about the validity and utility of some approaches, for example, the National Infrastructure Commission's reservations about cost-benefit analysis (National Infrastructure Commission, 2017b, p. 39).

There is an appetite for guidance about how much and what kinds of analysis are appropriate for different decisions (RALW, p. 29) and the Uncertainty Network recommended the creation of such guidance, especially in determining the scope and depth of analysis required (Uncertainty, section 2.1). This work could build on the taxonomy of decisions mentioned already to review appropriate decisions methods for different purposes, to explore what decision-makers need and use, and create guidance on how analysis can most usefully be presented. A review of decision approaches for climate change adaptation is exemplified by Dittrich, Wreford, & Moran (2016) and provides a candidate model for such thinking applied in this domain.

Note that it is often presumed in scoping analysis that the data, relevant and validated models, tools and virtual infrastructure exist to deliver such analysis. Such presumptions may be flawed. This further emphasises the significance of the simulations pertinent to the decision in question and coupled with decision support capabilities.

Decision processes will underpin this capability, especially to support and drive dialogue between decision-makers, analysts and stakeholders, together with competence in the creation and use of the full panoply of tools, for example how best to use scenarios rigorously (Uncertainty, section 2.9). The capability to build, choose and use wisely such tools will, ultimately underpin the capability to make good decisions within digital built Britain. Multi-disciplinarity matters, especially when decisions span sectors, and there are well-explored barriers to overcome in order to achieve this in practice (Howarth & Monasterolo, 2016). Focused work into the use of research evidence in decision-making gives insights into effective practices and how evidence-based decisions can best be supported (Langer, Tripney, & Gough, 2016). Other researchers explore the politicisation of the use of evidence and the relationship between the framing of the decision to be made and the collection and analysis of evidence in support of the structuring of the decision and the process by which it is to be made (Parkhurst, 2017).

Understanding the nature of the decisions, providing guidance in how to scope modelling and analysis and providing evidence of the value of the analyses are critical to building and embedding this capability.

G5.2 Discern, measure and communicate outcomes in major digital built Britain projects

Some critical parts of the creation of digital built Britain will depend upon 'mega-projects'. However, megaprojects have a bad press (Flyvbjerg, 2017) with many emotive stories of cost overruns and delays and relatively few countervailing viewpoints (McKenna, 2017). For digital built Britain to develop effectively, there needs to be more nuanced and insightful presentation of such projects that better communicate the richness of the term 'success' and the dimensions of assessment beyond just cost and timescale. As with smaller scale projects, major public infrastructure and construction projects require an initial identification of stakeholders and their needs, particularly where proactive stakeholder management practices will be used to improve project outcomes (Di Maddaloni & Davis, 2018).

Another dimension to be addressed here is the nature of the emerging narratives, especially when they arise from contested expert opinions tending to different outcomes (Dudley & Banister, 2018, p. 2). The definition of success and the data to demonstrate it, especially in large and visible projects is already a topic of intense academic debate likely to continue for some time (Flyvbjerg et al., 2018; Love & Ahiaga-Dagbui, 2018).

The call for shared data and information offers the opportunity to benchmark large projects (G1.4), their outcomes and the keys to success. However, the narratives that emerge about project outcomes also have a profound impact on perceptions of those outcomes as successful or otherwise. In some instances, as a project has unfolded there have been significant increases in the information available, objectives and criteria evolve, and sometimes new options become available. The freedom to embrace such options and to access the benefits available may be constrained as much by perception as by fact. Therefore, identified by the Uncertainty Network, there is a capability needed to better discern, measure and communicate the outcomes of projects in ways that better serve the needs of the UK, rather than being dominated by a specific narrative motivated by another agenda (Uncertainty, section 1.1). Primarily, it is about considering what the Network calls 'processes of success' and avoiding naïve and binary descriptors.

This suggests components such as:

- Define project boundaries (within systems of systems contexts) to formalise modelling and data collection in the assessment of project performance and success
- Articulate definitions of success
- Explore elements of uncertainty and the use of contingency funds to deliver outcomes
- Integrate the quantified and intangible while accounting correctly for externalities (Uncertainty; UIL a, section 3.3.4)
- Manage and integrate perspectives by which value is assessed
- Reconsider the timescales over which 'success' is defined and measured.

Work has been done in this domain, including thinking about the definitions of success (Global Infrastructure Initiative, 2018), reviews of success factors from different perspectives (Mišić & Radujković, 2015), exploration of how organisational structures and negotiation of evolving deliverables affects the narrative (Lundrigan, Gil, & Puranam, 2014), and the definition of new explanatory frameworks (Lehtonen, 2014). The Infrastructure Projects Authority has also published a guide to best practice in data collection and analysis in benchmarking big projects (Infrastructure and Projects Authority, 2019). These strands need to be drawn together.

The success of digital built Britain needs the UK to develop a more nuanced understanding of success, its determinants and its communication in order to not only deliver the vision, but also to represent its development more fairly along the way.

LEARNING AND ADAPTATION: Learn and develop the capabilities necessary to create and flourish in digital built Britain

The introduction below provides an overview of the **Learning** category of the Capability Framework for creating a digital built Britain.

Click here for an introduction to the **Capability Framework** as a whole, including links to all the categories involved.

Learning and adaptation capabilities

Understand the capabilities needed to create and flourish in digital built Britain

- Understand and characterise barriers to adoption (L1)
- Define the competencies needed (L2)
- Maximise learning opportunities and value capture (L3)

Introduction

Creating a digital built Britain will involve a continuously evolving process of learning and adaptation as part of a process of change for all within digital built Britain. Much of this change can and should be deliberately managed.

While there is considerable enthusiasm for digitalisation - some might say hype - adoption and exploitation of the opportunities it offers have been fragmented and piecemeal. If the power of digitalisation lies in the integration and co-ordination of collaborators along a supply chain, from the client, or consumer, through the network of providers and suppliers, then breaks in that chain must be avoided. We therefore need to understand the barriers to adoption throughout networks of collaborators, as well as in individual organisations, in order to help with learning and adaptation.

All users will need to develop the capabilities to use data better and to make educated decisions about their engagement with, and navigation of, the digitally enabled built environment and its services. The UK must meet the changing needs of its citizens by building new digital skills and literacies, into formal education and into training for adults in and outside the workforce. Companies will need to understand how to use digital tools, both strategically and operationally, to access new opportunities and to enhance profitability. We also need to understand the changes in activities, in jobs and in roles that will arise from digitalisation. Fundamental to this is understanding what competencies people will need to perform effectively and then deciding how best to teach and enable them.

Competency frameworks offer a way to describe and characterise value-adding activities in a world of changing job roles. Such frameworks could perhaps enable a more flexible work force and, by changing the focus of AECO from construction to digitalisation, encourage more young people to enter these sectors. Organisations will need to decide how to help their staff and managers to acquire these new skills, while the universities and professional associations must also keep pace with digitalisation. Embedding awareness of security issues at all levels will be essential to ensure a safer future in a world of ubiquitous data.

There are already many projects, case studies and demonstrators concerning the impact of digitalisation on the sector. More will be developed, but we need to be able to maximise the insights we can derive from these and from future projects, and to find ways to disseminate them more widely. Importantly, we also need to find ways to make such early work sustainable beyond its initial timeframe and funding, both to ensure learning continues and to prove the value proposition behind digital built Britain.

L1 Understand and characterise barriers to adoption

When it comes to adopting digital technologies such as BIM, digital twins and decision support platforms, not everyone is willing or able to immediately engage. Technical and non-technical barriers to adoption are frequently discussed throughout academic and grey literature, indicating a high level of interest and activity in this area. Gartner, Ernst & Young, Deloitte, and other technology-focused consultancies frequently produce articles surveying C-suite business leaders about their digital maturity, digital strategies and digital downfalls. These articles enumerate various reasons why, despite acknowledging the potential benefits, many are reticent about investing in data analytics, decision support platforms and other technologies (e.g. Blosch, Raskino, & Scheibenreif, 2018), or are not seeing the results they had expected (e.g. Kane et al., 2019).

Industry bodies have explored both the adoption gaps and the skills that will be needed within the industry to adopt new digital technologies, highlighting the need for soft skills, for support along the supply chain and the competing investment priorities (CITB Research, 2018).

The Gap Analysis produced for this project found that academics have also explored these issues. Technical barriers identified in this literature include the lack of interoperability (Andriamamonjy, Saelens, & Klein, 2019), lack of trust in data security and quality (Fathy, Barnaghi, & Tafazolli, 2018), predictive modelling for risk (Cerè et al., 2017) and contextual factors such as climate change (Chong & Wang, 2016), and a lack of tools for data verification (Whyte, 2016). Airaksinen et al. (2016) point to lack of stakeholder input, lack of clear data regulation, lack of ROI for environmental protections and a mindset of short-term planning.

Indeed, human barriers such as organisational culture, lack of leadership or resource, fear and reluctance are common threads throughout many papers (e.g. Alreshidi, Mourshed, & Rezgui, 2018). While much of the grey literature from consultancies focuses on barriers faced by industry leaders, Dainty et al. (2017) point out that there are barriers specific to SMEs arising from their smaller size, greater dependence on collaboration within their supply chains and the greater risk represented by investing in digitalization. While barriers to adoption are frequently discussed, barriers to capturing value from data analytics are less well-understood (Akter et al., 2019). Research may help unpack these barriers to enable a better understanding of how organisations can derive value from their investments in data and modelling capabilities.

While digital built Britain will be enabled by a wider range of digital technologies and processes than just BIM, understanding barriers to BIM implementation is a useful microcosm. Alongside the cultural barriers listed above and project-specific barriers highlighted by Laymath (2014), there are specific technical challenges to implementing BIM. According to a UK-based case study in 2014, the supposed technical barriers such as lack of maturity were less than anticipated. However, integration of BIM with FM needs to be better understood, and inter-organisational interoperability was identified as an ongoing issue (Kiviniemi & Codinhoto, 2014).

Despite this widespread discussion of the various barriers to adoption, solutions are not evenly or widely distributed in industry. This suggests that other mechanisms may be at work beyond those identified in the studies and papers discussed above. For example, it could be that when organisations do come up with solutions to barriers, they are not disseminated in papers but rather spun off or protected as proprietary. It is also likely that one size does not fit all, and a solution developed by a large digital leader will not suit the needs of SMEs that are sprinting to catch up, for example. Additionally, the issues discussed in the section on investability (V3) regarding the temporal off-set of benefits from investment may be at play here. Even when organisations are aware of the potential benefits of digitalisation, they may not be able to invest if the financial returns are decades away. Whichever of these are true, demonstrators, case studies and pilots will be instrumental in making solutions and benefits transparent across the AECO sectors. This would help identify potential incentives to ensure short-term investment in BIM, digital twins and other decision-support technologies.

Technical barriers such as interoperability, data quality and the predictive capacity of models are clearly areas where academic research will have a benefit, as discussed in the sections on smart asset management (B3) and on DATA. Barriers arising from human factors such as organisational culture, on the other hand, may seem more like an issue for industry to address. However, research could contribute to this area through demonstrators and case studies targeting common barriers to adoption in industry. Demonstrators are advocated by several of the papers identified in the Gap Analysis, including Abella et al. (2017) and Matarneh et al. (2019). Disseminating successes and failures as open access academic research, particularly if a common framework or set of assumptions is used, will ensure that others can learn from it. There may also be ways in which lessons can be generalised and yet further disseminated to commercial audiences to encourage adoption.

Demonstrators and case studies that use a consistent framework for evaluation would contribute to the growth of a comparable body of literature, enabling researchers to draw parallels and learn deeper lessons. For example, extending and developing tools such as Gartner's Digital Business Maturity Model (Iyengar, 2018), the BIM Level 2 Maturity Measurement Tool,[90] the Smart City

[90] http://www.ice.org.uk/knowledge-and-resources/best-practice/bim-maturity-measurement-tool

Strategic Growth Map tool (ESPRESSO & European Commission, 2016), or the maturity model espoused by the FOuNTAIN Network (section 2.2) could result in tools that could be applied to case studies and demonstrators worldwide and from various different sectors. This would enable academics to better understand, characterise and create solutions to common barriers to digitalisation.

While research, demonstrators and pilots can suggest ways of overcoming barriers to digital transformation, a common thread throughout most articles and papers suggests that education is at the heart of making the necessary culture shifts. Ensuring that there are skilled graduates entering the various sectors may mean changing the educational structures and systems available (PUN), providing incentives to data literate graduates to join the AECO sectors (Lamb, 2018, p. 10) and piloting innovative educational opportunities. Meanwhile, it is equally important to provide opportunities for growth and on-the-job learning to existing employees, and to provide the support necessary for them to pursue those opportunities (Kane et al., 2019). It is, therefore, essential to understand and characterise the barriers so that the right approach can be taken to dismantle them.

L2 Define the competencies needed

The move towards digital built Britain will place new demands on everybody, including residents and citizens, who will interact with the built environment and services in their daily lives, and policymakers, who must understand how to regulate digitalization, integration and development. However, much more change will be experienced by the professionals, organisations and leadership teams within the private sector. These are the people who will be striving to understand and make decisions about tools, trade-offs and outcomes and their capabilities are of utmost importance to delivering digital built Britain. This is the prime focus here.

The industry struggles with recruitment and retention of skilled staff and has already identified the need to focus on diversity and recruiting people with different viewpoints, as well as creating more meaningful work experience opportunities, co-ordinate training (Construction Leadership Council, 2018).

The numbers are striking: the Construction Industry Training Board (CITB) estimates that the sector will need to recruit and train 158,000 workers between 2018-22, which equates to about 31,000 per year. Brexit will erect barriers to employing non-UK workers, exacerbating the issue. In their Skills Strategy and Action Plan, the Construction Leadership Council (2018) identify a few imperatives around a future that is more digital and more driven by technology. For example, they call for, 'Programmes to retrain the workforce with the skills to support the future industry needs to embed and maximise the use of digital technologies and smart construction'. They suggest research, 'To highlight the potential scenarios for construction employment level in different occupations should the industry start to make more progress and move further towards application of new technologies and smart construction', and they focus on the digital agenda suggesting a review of digital platforms and tools in use today and with future potential and to explore what is needed to encourage adoption.

The industry leadership bodies are clearly supportive of the learning agenda around digitalisation, recognizing the need to engage with citizens and develop the professionals, organizations and the AECO sectors as a whole.

This can be broken down into the different capabilities needed by different stakeholder groups to navigate digital built Britain:

- Define competencies needed by citizens (L2.1)
- Define the needs for professionals and their development environment (L2.2)
- Define needs for management teams (L2.3)
- Define sector competence (L2.4)

L2.1 Define competencies needed by citizens

The magnitude of the change towards digital built Britain is laid out in the Government's Transformations Strategy, which, 'sets out how the government will use digital to transform the relationship between the citizen and state' (UK Cabinet Office, 2017). This intention, to make public services digital by default, sets the imperative for digital competence of people across the UK. The need for education and training to fill skills gaps is a commonly recurring theme in the literature and is frequently identified as one of the biggest barriers to digitalization in sectors such as construction and manufacturing (e.g. Deloitte, 2018; de Cicco, 2018). In many ways, the skills gaps throughout the AECO sectors are a microcosm of the wider 'digital divide' between those who can fluently interact with a digital world and those who cannot. Addressing the former requires first and exploration of the latter.

The digital divide is a term that reflects the gap between users and non-users of digital technology. The UN's and other strategic development goals include regular internet access and use as a fundamental marker of developed societies and, as recently as 2018, 10% of the UK's population fell under this threshold (Office for National Statistics, 2019). The percentage is higher for those over 75 years of age – in particular women (over 50%) - and those who identify as disabled (25%) (Office for National Statistics, 2016). Other factors such as childcare, incarceration, gender, income inequality, mental health and homelessness can lead to lower engagement with digital technology and a reduced likelihood of pursuing a digital career. The UN's 2018 survey provides not only statistics, but also useful reflections and case studies on the source of digital divides (United Nations, 2018b).

Non-users are the extreme and digital use and literacy is a spectrum, but the more reliant society becomes on digital technology, the more of that spectrum could be left behind. As access to services increasingly depends upon digital literacy, this becomes more critical. Even partial exclusion from digital technology can be profoundly isolating and impact individuals' ability to access basic services, engage with democratic processes, independently manage their finances and healthcare, access education and other essential actions. It also puts unnecessary strain on government resources.

Therefore, it is crucial when transitioning toward a digital built Britain to ensure that everyone learns the skills they need, that digital technology is inclusive and that barriers to use are reduced. Recent work has identified a collection of potentially interdependent barriers can affect whether individuals engage with digital technology:

- 'Access: the ability to connect to the internet and go online'
- 'Skills: the ability to use the internet and online services'
- 'Confidence: a fear of crime, lack of trust or not knowing where to start online'
- 'Motivation: understanding why using the internet is relevant and helpful' (Department for Digital, Culture, Media and Sport, 2017b)

A crucial first step to addressing this problem is to understand and map the digital divide in the UK with greater granularity. The ONS, doteveryone[91] and other organisations have led efforts to understand who is not online and why, but greater granularity would help tease out which populations engage more, and which engage less with digital technology. For example, while there is regional data about the digital divide, breaking this down by neighbourhood could give greater strategic insights. In the transition to digital built Britain, it is no longer sufficient that 84% of the population go online to send and receive emails (Office for National Statistics, 2019). Most people will need to use digital devices to do more and more daily tasks, jobs will increasingly require data and modelling competences, and everyone would benefit from greater digital literacy. Mapping where we are now will give us a better idea of how to get to a future where digital technology supports inclusion.

Considerable work has been done on the reasons for exclusion, on the characteristics of different user groups (e.g. older adults, rural populations, disabled people) and on the interplay between digital exclusion and social exclusion (Martin et al., 2016). Continuing this will enable a better understanding of both the symptoms and the causes. For example, there may be personal barriers to digital literacy, such as returning to work after a long absence, disabilities or a need for flexible working. These individual needs can represent substantial roadblocks to digital literacy and contribute to exclusion and isolation. However, digital platforms may be a route to digital skills development for some individuals, giving them flexibility to learn in their own time. Developing assistive and adaptive tools will make training material – and digitalised workplaces – accessible to a wider range of people, e.g. screen readers, sip-and-puff (SNP) navigation devices and prostheses. This will open the doors to developing a more diverse workforce. Innovative ways of delivering teaching and training, including hackathons, peer support, job shadowing and blended learning could further reduce the employee training bottleneck in organisations (Griffin et al., 2018).

While there are particular demographics that are disproportionately excluded from digital technology, it is not safe to assume that everyone else is completely at ease with it, even demographics commonly associated with high engagement. 'Though young people are often thought of as "digital natives", according to a recent Capgemini study, almost half of senior decision-makers do not believe young people know how to use digital skills for work' (Department for Digital, Culture, Media and Sport, 2017b). While many young people may be more frequent users of social media and streaming services than older adults, this does not guarantee that they inherently possess the skills and literacies that are needed for living and working in a digital built Britain. However, it

[91] https://doteveryone.org.uk/

may suggest routes to developing these skills and literacies, such as the gamification of digital literacy training and on-demand training.

The education that is available needs to be better targeted on the needs of employers (again, across a broad spectrum) and on the jobs to be done. Issues can occur even in the most apparently relevant of disciplines. 'At present, the UK has a supply of specialist skills that scores well above the EU average, but there are still significant improvements that must be made. For example, despite the growing need for workers with specialist digital skills, computer science graduates have the highest unemployment rate of any degree course at 10% after 6 months graduating, which is in part due to some graduates not leaving with the technical or professional skills needed by employers. To tackle this and the other specialist skills challenges, we are taking action across further, higher, and employment based education.' (Department for Digital, Culture, Media and Sport, 2017)

This issue is addressed by the UK digital strategy[92], which states that:

> *We will build on this work over the coming months by:*
>
> - *Taking forward the key recommendations from the Shadbolt Review of Computer Science Degree Accreditation and Graduate Employability. In particular, we will seek to increase the number of students undertaking work experience to develop their professional skills and will develop a revised degree course accreditation system.*
> - *Developing a common digital skills language to help industry articulate the digital skills they are seeking in a widely understood way and to provide digital careers information in a way school children and graduates can fully understand.*
> - *Working with the Data Skills Taskforce to help implement key elements of the Analytic Britain report - Securing the Right Skills for the Data-Driven Economy, which makes a number of recommendations on data analysis skills.*

But what skills are needed? What competencies and literacies must people have to flourish in digital built Britain? It is estimated that 90% of jobs will require digital skills within two decades (Department for Digital, Culture, Media and Sport, 2017b). However, the digital skills required will vary widely. Building on the basic individual digital capabilities, workplace skills will allow individuals to be productive and flexible in their careers. Developing these skills will range from learning to use emerging technologies, e.g. immersive technologies, smart badges, virtual assistants and digital workspace apps (Cain & Woodbridge, 2018), all the way to developing the competencies to use data and digitalisation to make better decisions.

The competency profile of the individual in digital built Britain will not be static, hence upskilling and reskilling through life will be as critical as foundation education as people build and migrate from one competency set to another through education, training and experience (PUN). Two key issues

[92] http://www.gov.uk/government/publications/uk-digital-strategy

emerge in targeting training and development programmes for the public. The first is to avoid exclusion that may arise as a result of the 'digital divide', while the second is about tailoring current education to the needs of employers.

In coordinating the targeting of learning to support the populace, it is important to understand the ecosystem and to have framework that can act as tool for thinking and as a language for discussion, debate and development. NESTA have identified components of the development ecosystem and provide guidance that is specifically related to elements of that ecosystem (Orlik, 2018). Their guidance also includes case studies which provide practical examples of ways to address each of the elements of the ecosystem. The NESTA work is delivered through Readie[93], an alliance for research and policy into the digital economy.

There are many frameworks which aim to address different aspects of the learning agenda. For example, The UN's 2018 survey (United Nations, 2018b) itself provides a view of a candidate framework for assessing how citizens may or may not access key services.

In terms of the skills needed, there are various existing frameworks targeted at the public need and more are being developed as digitalisation progresses. The Department for Education gives guidance that looks to promote digital inclusion by outlining an essential digital skills framework (Department for Education, 2018), which covers the basic skills that all adults in the UK should have. Organisations such as doteveryone and the Good Things Foundation[94] are working on making this happen through education, training and outreach. Many competency frameworks exist aiming to characterise the needs of citizens in a digital future, for example the EU's Digital Competence Framework[95] and the Common Framework for Digital Literacy, Skills and Readiness (DQ Institute, 2019). Others target specific areas, for example in data protection for students (International Working Group on Digital Education, 2016) and more. There are also frameworks that go beyond basic skills to define data, information and digital literacies. These encapsulate a deeper understanding that individuals should have to be truly fluent in a digital world. One example, the SCONUL '7 pillars model' of information literacy, outlines interdependent and dynamic capabilities needed to identify, scope, plan, gather, evaluate, manage and present digital data and information[96].

Other frameworks address digital maturity rather than literacy. Digital maturity exists on a spectrum that is frequently broken down into stages, e.g. 'early', 'developing' and 'maturing' as proposed by Kane et al. (2018). Each phase has its own skills requirements so learning and development strategies should grow and change with the needs of users. Yet others specifically consider the needs of citizens within smart cities, the 'Digital Citizen Engagement Framework', and address the engagement between the user and the services within the built environment (Krishnan et al., 2018).

The competence of individuals within the workplace must also be addressed. 'While awareness of the data literacy challenge is emerging, only a few techniques and providers of data literacy assessments and training in the workplace have emerged in the market. Lack of common models or

[93] http://readie.eu/
[94] http://www.goodthingsfoundation.org
[95] http://ec.europa.eu/jrc/en/digcomp
[96] http://infolit.org.uk/definitions-models/

frameworks and siloed, localized training approaches are critical obstacles for rapid and widespread adoption globally. The lack of comprehensive data literacy programs, standards, training and certification inhibits awareness and adoption.' (Cain & Woodbridge, 2018)

To address this fragmentation, NESTA argues for a skills map (Sleeman, 2017) and have explored this with a prototype tool that maps out the skills needed in many jobs, derived from monitoring and sampling job adverts. Their tool explicitly explores the extent to which technology is key to the various jobs[97]. Mapping digital skills among the general population has already been done at the government level as part of the UK Digital Strategy (Department for Digital, Culture, Media and Sport, 2017b). These large-scale mapping activities, done at a finer degree of granularity could be scaled up to produce predictions about national competency needs based on a range of digitalization scenarios and could be used as a common language by educators, organisations and students.

Building such maps and frameworks will be essential in order to map out the landscape of competencies needed, and also to create a common language which can be used to discuss plans and priorities for the development of such skills across digital built Britain. As seen elsewhere in this document, there are numerous existing frameworks, but it is not clear that any of them will help with the articulation, assessment and delivery of the targeted support that citizens will need to engage with digital built Britain. The development of such a framework is a topic for further research.

Above and beyond the frameworks to develop prioritised agendas for learning and development, there are key capabilities which are already evidently important for everyone in a digital built Britain to possess. Chief among these is security mindedness. Individuals in digital built Britain will need to understand issues around data security, pertaining both to their own data and to any data they might use through work. Malicious attacks (spear-phishing, malware, account hacks, fraud, etc.) are likely to get more advanced and harmful, so it is important to continue to educate individuals in how to stay safe online. Of course, the safety so engendered applies not only to the individual, but also to their families, their workplaces and, by implication, to the services and assets of digital built Britain. This is brought to the fore by the Centre for the Protection of National Infrastructure in their guidance[98]. However, unless there is a coherent context for important skills such as these, there is always the risk of it being a marginalized message among so many others.

L2.2 Define the needs for professionals and their development environment

This section turns to focus specifically on the capabilities that will be needed to continuously develop skills and the ability to adapt as new requirements demand new skills specifically among professionals in the AECO sectors. Demand for skilled employees in these sectors are set to grow

[97] http://data-viz.nesta.org.uk/skills-map/index.html?_ga=2.266260233.744281373.1556710277-2075038597.1551355206
[98] http://www.cpni.gov.uk/my-digital-footprint

over the next five years (e.g. HM Treasury, 2015). This presents a challenge to employers, as competition for skilled workers will increase, without much promise of the workforce being able to meet the need. Meeting this challenge may involve working with schools or universities to develop curricula that develop the right skills, creating digital training materials and/or developing an individually focused teaching strategy (PUN, Appendix: Research Questions – Question 7). For example, in contrast with traditional, didactic workplace training, giving employees co-ownership over their own development can foster better engagement and retention rates (Griffin et al., 2018).

This ownership message is repeated elsewhere. The Pedagogy and Upskilling Network call for more demand-led competency development (PUN). This must entail the individual practitioner understanding the criticality of gaps in their competence set and being motivated to fill such gaps. The continuing evolution of technology should drive a continued demand for upskilling throughout the career of those working in the sector and thus a demand-led approach to provision.

Digitalisation requires digital skills. 'Data and its effective collection, communication and management are central to digital transformation. Industry needs to demystify how data is used and the skills required across the entire workforce. Genuine understanding of what data management involves is limited.' (Construction Industry Training Board, 2018). However, the BIM experience teaches us that there is even greater emphasis on softer skills as digitalisation proceeds (Construction Industry Council & BIM2050, 2014) and especially on complex projects (Gale et al., 2010).

Define and develop competency frameworks within sector ecosystems

Attempts to structure the knowledge needed by construction professionals already exist. For example, the Construction Management Body of Knowledge (CMBOK) outlines a framework of skills and understanding that unites the various strands of construction management including construction informatics, automation and delivery of complex projects. 'The cognitive framework of construction management body of knowledge can also be useful to inform higher education, professional training, as well as academic and professional research in terms of well-scoped depth and long-term continuous professional development. It is therefore considerate to develop a cognitive framework of BOK for the construction management profession.' (Chen, 2019)

There exist competency frameworks that drive into specific domains in using data and models, for examples, see the Government statistics competency framework[99] and Code of Practice[100]. The Construction Industry Training Board (CITB) fund research and projects that aim to grow capabilities, and they do this strategically, based on evidence and mapping (CITB, 2019).

Central to the provision of skills to professionals facing increasing digitalisation will be to organize it in ways that enable debate and discussion, comparison and agreement and, ultimately to enable professionals and their employers to speak a common language in the creation of relationships and

[99] https://gss.civilservice.gov.uk/policy-store/competency-framework-for-the-government-statistician-group-gsg/
[100] http://gss.civilservice.gov.uk/policy-store/code-of-practice-for-statistics/

contracts. Note that the same construct could also apply to discussions between organisations across a supply ecosystem to discuss the competencies needed by specific projects.

This need was recognised by the CITB (2018) recommending that, 'Digital competence requirements across the built environment sector are standardised and embedded in qualifications, training and employer HR planning,' and that, 'Training is available and undertaken to deliver standardised competencies across the sector, both as part of formal qualifications and continuous learning.'

The concept of a competency framework is at the very core of the recommendations of the Pedagogy and Upskilling Network and is laid out within that report (PUN, section 3.2), together with proposed research questions and candidate approaches. The Network lays out research questions for the short, medium and long term. Their proposal for immediate research (*ibid*., p. 26) includes exploring how a '"collaborative competence management" approach might be designed and implemented that enables/facilitates competence as a currency in the labour market', understanding the implications for curriculum development, and the tools to empower individuals to manage their own competence profiles.

For the medium term (3-5 years), they suggest deeper research into more profound questions such as how competence evolution might lead to agility and resilience in the workforce. Beyond that, they suggest exploring yet more fundamental questions about how to enable individuals to thrive in the workplace, but this seems more generic than specifically related to digitalisation and may be able to draw upon other research resources from different disciplines.

A competency framework, this time focused on BIM, was the recommendations arising from work for the Scottish Futures Trust (Bush & Robinson, 2018). They identify and characterise several current competency frameworks and make recommendations for a way forward.

Note that the Pedagogy and Upskilling Network specifically recommend a framework based on professional activities, as distinct from the role-based framework suggested by Bush and Robinson (*ibid*, p. 32). The Network argues that an activity-based approach is more robust in a world where roles and jobs are changing and especially as jobs are transformed by new technologies. This reflects the changes seen in the introduction of BIM (Mathews, 2015).

The level of detail in such frameworks matters. The Pedagogy and Upskilling Network point out that, 'Proxies used for competence supply and demand are no longer either granular or dynamic enough for the changing world of work.' This leads to problems not only with negotiating skills that are needed and available, but also in the whole matter of supply and demand. (See also the previous subsection, L2.1, for a comment on demand for more general digital skills.)

Define needs in teaching and development

Turning now to the supply side of teaching, training and development skills, there are both opportunities and challenges from digitalisation across the sector. The Pedagogy and Upskilling Network highlight issues of discipline silos, arising in part from patterns of accreditation and the need to balance the research and teaching agendas, especially around vocational training (PUN, p. 21).

Such concerns may predate the emergence of digitalisation and yet be exacerbated by its demands. For example, work from 2013 (Bordass & Leaman, 2013) and from 2014, the Edge Commission Report on the future of professionalism in the sector, Morrell (2015) provides a rich context and explains the issues.

The very concept of professionalism under the influence of digitalisation has been explored by Jaradat, Whyte, & Luck (2013). Yet others (e.g. Hughes & Hughes, 2013) have researched the role of professionalism and the professional institutions, specifically in the context of the planning and development of the built environment.

Others are looking at the beliefs and expectations of student in the early years of their university degrees and faced with the imperatives of Industry 4.0 (Motyl et al., 2017). Although set in an Italian context, it seems likely that many of the messages are transferable to the UK in an increasingly internationalised world.

There are several strands of research into the implications of digitalisation in the teaching of professionals in the sector. There is a long history of research into educating architects in the context of BIM (Berwald, 2008; Benner & McArthur, 2018), which covers, for example, concerns about creativity and innovation all the way to the use of models and simulations. In the UK, research is being conducted at Brighton (Jin et al., 2018), exploring BIM as a collaboration platform, at London South Bank University in teaching practices (Adamu & Thorpe, 2016), and researchers at both UCL (Perez-Martinez, 2017) and Robert Gordon University[101] are exploring future directions in pedagogy.

Acknowledging the issues associated with encouraging young people into the industry, the CyberBuild Lab at Herriot Watt worked with Skills Development Scotland (SDS), the Construction Industry Training Board (CITB) and Animmersion Ltd have explored use of virtual reality and gamification to create tools (Cyberbuild, 2019) to help promote career opportunities in the construction industry.

These strands are currently largely independent and there may be value in linking them, others, and new initiatives to the competency framework proposed above.

Define needs in competence assurance

The Pedagogy and Upskilling Network (PUN) note specifically the need to build capabilities in competence assurance (including technologies and processes) to intelligently manage competences, people and work activities. These assurance capabilities must reside not only in the employing organisations, but also in the educational and the professional institutions.

They go on to note that, 'There is still a considerable lack of ecosystem to facilitate curriculum management', advocating that it be 'competency-based and demand-led'. They go on to describe both the ecosystem and the infrastructure that would be needed to enable and to work with their proposed competency framework in order for everyone to manage supply, demand, acquisition and

[101] http://www.rgu.ac.uk/research/research-degree-topics/1069-pedagogy-in-architecture-and-built-environment

assurance of the required competences. Competency analytics become the next step (*ibid.*, section 3.4).

They argue also that academics and their academic institutions must also assure their own competence to educate, to train and to assure, at whatever degree of granularity proves most useful. Furthermore, this must extend to though-life training and education, continuing professional development and upskilling.

The role of HEIs and the changes needed are discussed by PUN (*ibid*., section 4.1), highlighting needs for greater focus on interdisciplinary working and imparting leadership capabilities, while reflecting upon the difficulties in curriculum change. They also note the needs for significant culture change and the vital importance of individuals taking a lead for change.

The Network also highlights the need for professional institutions to embrace broader perspectives to cater for the wider needs that will be imposed by the evolution of digital built Britain (*ibid*., section 4.2). This is entirely consistent with the convergence of sectors, which will develop as integration between services, assets and business models proceeds.

All of these issues apply not only to initial education but also to continuing professional development (CPD), especially in the face of career-long developments in roles, activities and enabling technologies. The fragmentation of provision of CPD only exacerbates the situation. The HEI sector is developing mechanisms for discussion and coordination such as the Council of the Heads of the Built Environment (CHOBE)[102], likely to be a very relevant stakeholder.

L2.3 Define needs for management teams

Here, the capabilities that need to be developed by the management of organisations are considered. The section first regards the ways in which skills are to be identified and developed. Attention will also need to be paid to the changes that digitalisation will inspire within organisations' processes, structure and culture. It then goes on to consider the implications of digitalisation and skills across the supply chain, which makes up such an important part of an organisation's capability. Finally, it touches on a specific point about the new demands on client competence in an ever more digital world.

The Pedagogy and Upskilling Network (PUN) see increasing issues in supply and demand within the sector, and this is reflected by others. Research indicates that recruitment alone is not sufficient to fill gaps in digital skills and literacies. Therefore, organisations should focus more on teaching and training for existing employees that is flexible, accessible and supported across all levels (Griffin et al., 2018).

However, the Pedagogy and Upskilling Network also see the emergence of an ecosystem based on the effective mediation of competence supply and demand within the construction sector and wider

[102] http://chobe.org.uk/

built environment as being central to building the sector's capability to learn and adapt. In their report, they note the need for an ecosystem mapping (*ibid.*, figure 2), noting that this may need to extend beyond the boundaries of the industry because of the incoming solutions and value propositions as other sectors convergence upon digital built Britain. Note also that this mapping will need to be done at the correct level of granularity in order to make development, update and adoption effective. Failing to get the right granularity promises the same mismatch as reported above about computer science graduates. The rate of change exacerbates the issue because competency profiles are constantly changing, creating a huge challenge in meeting demand for a rapidly diversifying range of skills in the AECO sectors (Morello, 2017).

It is important to note that this is not, primarily, about pure technical competence. Softer skills and adaptability will be as important in many activities (and roles). 'Tech-specific skills aren't the problem – but broader skills and competencies at various levels need to be addressed. Leaders need skills in implementing digital change and creating the right structures and culture. Managers and operatives need problem-solving skills and greater digital savviness. Not everyone needs to be at the same level. It's about enabling top-down and bottom-up change.' (Construction Industry Training Board, 2018)

The scope of the ecosystem that needs mapping includes the supply chain, together with many other key players. As commented elsewhere (B4), investment in digital technologies is proving more challenging for SMEs, especially once issues of training and workforce development are included. The mapping of the ecosystem, aligned with a coherent competency framework, should prove a useful management tool as organisations seek to articulate their needs for skills and literacies throughout their organisations and decide where and how best to invest in learning (Griffin et al., 2018).

Organisational processes, structures and cultures

Organisations have already found that they need to revisit their organisational processes as they adopt BIM (Kokkonen & Alin, 2016). This will continue at accelerating pace, scope and depth as digitalisation unfolds. This also goes to the heart of the difference between digitisation (digitising what you previously did in an analogue fashion) and digitalisation (exploring how data, information and digital tools could enable entirely new and better ways of working). This is explored further within the section on better understanding through data (D1).

Client competence

One of the most powerful drivers within the entire supply chain is the client's behaviour (B3). Hence, this is a key point of leverage to accelerate towards digital built Britain and client competence becomes an issue. The Pedagogy and Upskilling Network note that 'clients themselves require certain competences in order to fulfil the activities associated with their role' (PUN, section 3.2). Guidance exists that covers a broad range of issues (RICS, 2015), and research is being conducted in, for example, the assembly of BIM supply chains (Mahamadu, 2017).

L2.4 Define sector competence

Sector leadership will be a key driver of success in the transition to digital built Britain. In large part, however, this is not a topic for research but rather one of industry leaders aligning their will and objectives in the articulation and pursuit of shared goals.

Sector leadership bodies abound, including the Construction Leadership Council (CLC); Construction Industry Council (CIC); Construction Industry Training Board (CITB); Institution of Civil Engineers (ICE); Royal Institute of British Architects (RIBA); Chartered Institute of Building (CIOB); Chartered Institute of Architectural Technologists (CIAT); Chartered Institution of Building Services Engineers (CIBSE); Institute of Workplace and Facilities Management (IWFM); Highways Term Maintenance Association (HTMA); Civil Engineering Contractors Association (CECA) and BuildUK. Each organization has its own remit for teaching, training and advocacy, but most should be able to agree on a common set of values in order to maximise skills development potential. Consensus among these organisations about the broad outcomes will enable them to pursue and promote an aligned selection of skills and practices, roles and regulations needed in digital built Britain.

The Farmer Review (Farmer, 2016) concludes that the CLC need strategic oversight to oversee change, including the reform and redevelopment of training by CITB. In their view, these sector bodies are part of a cooperative relationship: ‘At the heart of these recommendations is the need to establish a new “tripartite covenant” between the construction industry, its end clients and government which leads to mutual benefit for all parties. The aim is to bring about a step-change in investment in skills and technology across the industry.’

In response to the Hackitt Review, the implementation plan ‘Building a Safer Future’ is a current example of industry engagement and leadership with respect to wide-ranging issues of competence (HM Government, 2018a). Note, for example, the ‘Early Adopters’ working groups in competence (*ibid.*, paragraph 2.12) and in the adoption of the digital agenda combined with collaborative working across the supply chain (*ibid.*, paragraphs 2.28-29). This is also indicative of an industry responding to the Farmer Review call for new ways of working.

Sector leadership needs also to have strategic oversight of digital skills and literacies to ensure digitalization is enshrined at all levels. According to the Construction Industry Training Board (2018), standardisation and embedding of these principles should be grounded in a common understanding of value, ‘common goals and a plan of action to increase digital skills in line with ambitions for digital transformation throughout UK construction’. This could be accomplished using leadership bodies and professional institutions to incentivise good practice. Sharing lessons within and between sectors will help grow the national stock of knowledge about what does and does not work in terms of digitalisation in various context. Finally, sector leadership should provide routes to learning and development of digital competence across supply chains. Business and management research projects might inform practice in these areas and map the ecosystems of sectors to identify barriers and levers to learning and development of digital competencies.

The Pedagogy and Upskilling Network (PUN, Executive Summary) comment on the paucity of sector-wide initiatives, with the people-centric focus necessary to deliver the change envisaged. They note also that competency development will be a greater challenge for the industry than will technology, reflecting the balance of barriers to adoption seen in the literature discussed in section L1.

Supply chain competence

Development of the capacity of the supply chain to learn new skills and to adapt will be vital. Building relationships between partner organisations that are contingent on trusted flows of data and information will enable the 'golden thread of information' (Hackitt, 2018a) that supports safety, efficiency and value in the built environment.

The Pedagogy and Upskilling Network (PUN, Executive Summary) note specifically the need for interacting parties to share a view of the competences needed across the many intersecting and interacting activities which make up the increasingly complex projects that characterise today's construction industry (*ibid*., p. 14). This becomes even more important as the impact from any skills shortage multiplies its effects all the way up the supply chain to the end client and the value of the project itself. The digital competence of a supply chain is only as strong as its weakest constituent (Hurtgen & Mohr, 2018).

L3 Maximise learning opportunities and value capture

The transition from the Britain of today to the digital built Britain of the future will be characterised by continuing change management, of wide scope and considerable depth. Certainly this has been the experience within other sectors undergoing digitalisation on a large scale, for example in aerospace (Lamb, 2018b). However, it is not clear that this requires specific research, there being many practitioners with experience in supporting change management standing by to help when called. Therefore, this document focuses on the topics revealed to be troublesome – valuing the ability to learn, knowing what to learn, and coordinating learning across stakeholder communities.

In a 2015 report, the Tinder Foundation and GO ON UK[103] unpacked the potential economic benefits of digital skills (Hogan et al., 2015). Projecting the benefits of a national digital literacy rate of 100%, they categorised these as:

- **Employability**: 'By 2025, it is estimated these benefits will amount to £204 million per year in net earnings and £79 million per year to the Government in the form of Jobseekers Allowance (JSA) savings and increased income tax and NI receipts.'
- **Spending power**: 'We estimate transaction benefits to individuals of £796 million per year by 2025.'

[103] Now called the Good Things Foundation and doteveryone, respectively.

- **Time savings**: 'By accessing government services and online banking transactions online, individuals can save an average of 30 minutes per transaction… Our calculations show that these time savings would provide benefits amounting to £1.5 billion per year by 2025.'

Their conclusion was that investment of £14.3 billion in digital skills would provide a cost-benefit ratio of 9.7, or nearly £10 of economic benefit for every £1 invested. This is compelling evidence for government investment in basic digital skills throughout society. However, such analyses do not scale to the individual firm trying to evaluate the return on their own investment in training.

In the professional and organisational spheres, currently the UK spends 0.01% of GDP on worker training, 'whereas Germany invests 20 times this and France close to 37 times that amount' (Shaw, 2018). This investment level demonstrates the relatively low value placed on worker training in the UK. If learning and development of digital skills and literacies are to become a priority, it is crucial to provide evidence of their short- and long-term benefits, and also of where and how those benefits are likely to accrue.

Such analyses are notoriously difficult because of the many confounding factors that are specific to each instance. Furthermore, different organisations are at different stages of their journey. It is this that underpins the Fountain Network recommendation (FOuNTAIN, section 2.2) for the UK to build the ability to 'gauge Information Management maturity, as part of existing standards or new standards'. Such a tool should be specifically designed to help guide organisations to the next step rather than simply providing a classification.

Furthermore, any analysis undertaken needs to very explicitly distinguish between value creation, value delivery and value capture. The significance of this has been highlighted in digitalisation and business model innovation by Parida et al. (2019). They show an analysis of value creation, delivery and capture, identifying past research activity and future research directions (*ibid*., figure 2).

By analogy, the same issues need to be clarified in the choice and extent of investment in learning. Who pays and who benefits? Who benefits in the short term and who benefits in the longer term? What costs are avoided as a consequence of greater competence and facility? What network or ecosystem effects develop and to whom do the benefits accrue? Only when these questions are answered can the value proposition be clarified for any given investor. And for the many SMEs in a low-margin industry, this value proposition will need to be compelling.

The opportunities for teaching and training within an education context are addressed within the section above. Below are examples of how to maximise learning opportunities and necessary capabilities to develop:

- Learn from projects, research and demonstrators (L3.1)
- Learn within organisations (L3.2)
- Learn from other sectors (L3.3)

L3.1 Learn from projects, research and demonstrators

Learn from projects

Currently, the construction industry is not making the most of projects by disseminating data and information. When projects begin in an ad hoc manner, or shift and change throughout, information can easily be mismanaged. Even if the data survives, knowledge and insights are not often shared, meaning that the industry is slow to learn from itself. This can lead to reinventing the wheel, or worse, repeating the same mistakes. CAR point out the value of sharing insights from projects (CAR, Executive Summary). One option, explored in the section on regulation (G1), is the creation of databases of project experience which can be interrogated for insight and lessons. The National Infrastructure Plan for Skills identify the same challenge, noting that we need to know how to ensure that 'skills built on current successful projects and required for future projects are not lost to the industry' (HM Treasury, 2015a).

This is a recognised imperative: 'Much tech that is being used is not at the cutting edge of what is available. Drones, Lidar, smartphones and tablets are increasingly widely used, but truly innovative tech – if used at all – is generally limited to small pilots or trials, as investment in larger scale innovations is considered too risky. Sharing best practice will help industry evolve understanding of the value of digital and the skills and training needed.' (Construction Industry Training Board, 2018) Therefore, the results of these innovative, leading edge projects should be better disseminated and evaluated more consistently to provide a comparative knowledge base from which everyone in the AECO sectors can draw.

Box 6

The Deloitte headquarters in Amsterdam, known as The Edge, is an example of excellent communication about a smart asset. The building has been covered in trade publications (e.g. BREEAM, 2016) and the wider media (e.g. Wakefield, 2016), as well as academic case studies (e.g. Jalia, Bakker, & Ramage, 2018). In part, this coverage has been orchestrated and abetted by Deloitte and the architects, PLP architecture, who derive immediate value from promoting the award-winning building.

Of course, it is easier to talk about successes so follow-up studies after years of occupation will be an interesting comparison to the early fanfare. It is striking to note that no downsides or disadvantages have been raised in the literature. So, while the early coverage provides an example of the art of the possible to others in the AECO sectors it does not provide any lessons in what to avoid.

Learn from research

Maximising impact from funded research has long been an imperative for the Research Councils and remains a continuing policy priority.[104]

Research projects are a natural way in which to spread this type of collective learning, provided they are disseminated in open access formats and captured elsewhere in plain language to act as a signpost that is accessible to those without specialist academic training. There appears to be little specific exploration of the interactions between the sector and academia, but Moncaster et al. (2010) note the need for new mechanisms, 'to facilitate the use and application of technical advances with social and public benefit that lack commercial merit, and therefore fall outside existing mechanisms'.

Researchers and funders need to consider explicitly how their work will be seen by industry. Relevance, applicability and barriers to adoption should be key topics. If at all possible, work should use real data and have a demonstration site in mind to confirm robustness and maximise the likelihood of acceptability (Vision). Early discussion of what is and is not commercially confidential is essential to enable the widest sharing possible of insights and lessons, and importantly, the ability to abstract and identify the principles of what has been learned as distinct from the specifics of the instance.

However, most transfer is predicated on immediate commercial return, and ARCC (2016) note the need for new mechanisms, 'To facilitate the use and application of technical advances with social and public benefit that lack commercial merit, and therefore fall outside existing mechanisms'.

Specific development of case studies with the prime purpose of communicating and showcasing new ways forward, such as the ones championed by CDBB (e.g. Jalia, Bakker, & Ramage, 2018), would help communicate case studies and demonstrators to a broader audience.

A domain not so far explored is how best to maximise the value of research conducted by industry participants under their own auspices and therefore, presumably, for commercial return. Are there ways by which broader value may be realised?

Although not explored here, there may be merit in researching how other sectors have maximised the value of their engagement with research, identifying lessons learned and addressing any attributes of the AECO sectors that raise specific difficulties. The Research Programme of CDBB[105] is, of course, dedicated to maximising lessons from relevant research.

Learn from demonstrators

Case studies and demonstrators can be a powerful way of sharing knowledge and insights, but too often they do not go deep enough into evaluating the case studies to be useful. A framework for publishing and evaluating case studies and demonstrators would help build a knowledge base for

[104] http://www.ukri.org/innovation/working-with-business/
[105] http://www.cdbb.cam.ac.uk/CDBBResearchBridgehead

the AECO sectors, wherein insights from different projects could be compared and broader understanding established.

EU research funding websites exist specifically to share such information – see, for example the Smart Cities Information System[106]. The Future Cities Catapult conducted a review of smart city demonstrators (Future Cities Catapult, 2019), drawing out general lessons and insights and making recommendations about future demonstrators. Others are looking at smart city initiatives with a view to creating a framework for the design of future initiatives (Ojo, Curry, & Janowski, 2014). Such efforts could be usefully disseminated, while the frameworks themselves enable more structured learning and dissemination.

There is considerable concern that there is not as much insight drawn from demonstrators as might be possible. Many seem to run as isolated projects and then cease, marked only by a report and a website. Some 'top-down' smart city ideas have failed to deliver on their promise, combining high costs and low returns (Saunders & Baeck, 2015). Therefore, given the magnitude of the investment, there is much to be gained from maximizing the learning that can be done. There are reports of 'demonstrator fatigue', a recognition that just proving a principle is not always enough to mobilise the market and a desire for better frameworks to help partners manage the extraction of lessons and benefits (UIL b, section 3.3.8). Others have highlighted the problem of such projects ceasing to operate when the funding stops, and proposed approaches to identifying the conditions needed for scalability and how best to scale up (van Winden & van den Buuse, 2017).

UIL surveyed the range of demonstrators created in the past four to five years for new smart city, smart energy, connected and autonomous vehicles, Mobility-as-a-Service and systems-of-systems (UIL b, section 5). They note the recurrence of the same themes across multiple demonstrators, without a commensurate increased level of adoption.

Plans for demonstrators should clearly articulate their purpose; to explore the boundaries of a technology (i.e. without certainty of success), to integrate previously disparate technologies to show the potential of such technologies as an integrated capability (i.e. with a focus on integration), or to illustrate commercially available capability (i.e. to 'sell' a capability to a sceptical audience).

To date, demonstrators have focused primarily on assets and their use. Given the importance of building capabilities in creating information-driven supply chains and ecosystems, there is value to be gained by building and learning from high-value use cases that explicitly explore contracts, data flows, and any examples of 'X-as-a-Service' propositions. UIL explore instances and recommend this as a form of demonstrator with great potential (UIL a, sections 5 and 7). Further work could be undertaken to better understand the implications of the coupling between services and infrastructure and certainly to explore the social as well as the technical. Importantly, UIL show how the demonstrators could be linked to capabilities they identify as critical, which are in turn covered across this report, and so identify the opportunities for learning (UIL b, table 16).

Integration of technologies is a vital role in demonstrators. For example, research projects that advance the integration of various other technologies with immersive technologies are required to

[106] http://smartcities-infosystem.eu/

show the full potential of AR and VR (Vision). As well as integrating technologies it is vital to integrate the partners into an ecosystem which can be seen to demonstrate financial viability in the real world, being a key to sustainability post-funding (UIL b, section 3.3.5).

One of the most important insights to be derived from demonstrators pertains to value – that created and that captured and where these are different in time, in space and in recipient. Unless this is done, the investability of digital built Britain will continue to be vague and elusive. (See also the section on VALUE.)

As well as applying structure to the extraction of lessons and insights from future demonstrators, there may well be relatively cost-effective benefit from applying the framework to completed or current demonstrators to i) test the concept and ii) extract more benefit.

Research to apply this Capability Framework could explore whether it might provide a useful and unifying tool to identify, to marshal and to disseminate lessons. In particular, the many perspectives and the explicit interlinking within the Capability Framework encourage the extraction of insights wherever they may be found.

L3.2 Learn within organisations

As well as considering the sharing of knowledge between organisations, there is yet much to be done within organisations. Leaders and managers need to know how to target teaching and training to provide employees with competency, mobility and support. The *MIT Sloan Management Review* and Deloitte's 2018 survey of digital businesses found common threads among those that ranked themselves as 'maturing': these leading-edge organisations invest in teaching and training their existing employees rather than simply relying on recruitment to meet skills and leadership gaps (see ***Box 7***). This emphasis on development means that these organisations can devolve decision-making, create a culture in which it is safe to experiment and foster their employees' professional development. From this same survey, 90% of respondents replied that they needed to update their digital skills at least on a yearly basis, meaning that ongoing organisational support for learning and development is crucial to meet the evolving need for digital skills (Kane et al., 2018).

Learning is not simply an issue of skills development. Transferring implicit and institutional knowledge within and between organisations in the AECO sectors is crucial

Box 7

Organisations in heavy manufacturing are aware of the digital skills shortage facing their sectors. According to Lineberger et al. (2018), 'As many as two million manufacturing jobs in the United States are likely to go unfilled between 2015 and 2025 due to the unavailability of skilled workers,' and the UK is likely to have a similar deficit.

To address this, companies like Boeing are getting involved in education. Boeing targets high school students through an accelerated upskilling and recruitment programme and partners with high schools, trade schools and others to develop a curriculum that builds digital skills.

to developing a digital built Britain. Leal et al. (2017) discuss many of the barriers to knowledge sharing in construction, pointing to a shortage of resources and cultural disinclination as key issues. They identify digital knowledge management (KM) platforms – and organisational cultures that value using them – as potential enablers of this type of institutional learning. The standards document *Introduction to Knowledge Management in Construction* (PD 7503:2003) provides guidance for construction firms wishing to develop or use a KM platform, but despite the availability of this information, time and money are still wasted due to implicit knowledge disappearing. Developing asset and service models that can capture this information will help retain institutional memory in the context of particular assets or services, but only if there are processes and cultures in place that mean this technology is actually used. Demonstrating the value of knowledge sharing, therefore, is an important step in order to encourage organisations to put these measures into place.

Within individual organisations and across the AECO sectors there are many potential methods for communicating and sharing knowledge about past projects. Communities of Practice, storytelling, mentoring and creating information in intranets can help develop cultures of knowledge sharing. These methods also benefit from creating opportunities for more general learning and development in organisations. However, in order to connect other stakeholders with knowledge and insights from the sector, broader dissemination should be used in addition to these more siloed fora.

L3.3 Learn from other sectors

Other sectors have embraced digitalisation in advance of the AECO sectors, typically because they have different value creation and capture opportunities. This means that there is considerable experience to be drawn upon from other sectors, but that care needs to be taken in translating these lessons. Issues such as cost points, margins and market power will all be different in different ecosystems. Indeed, the same is true within the AECO sectors. For example, the needs of nuclear infrastructure versus those of waste management mean that digital technology will be applied to address different problems in each.

But the potential remains to extract insights from others' experience with digitalisation (see, for example Lamb, 2018b, 2018c). Turner Harris explore opportunities and examples in learning from other sectors such as aerospace and automotive, marine and shipbuilding and retail (TH, p. 11). While the first all provide insights into the implications of management and creation of assets and services, lessons from retail could especially provide foresight of emerging social norms and expectations pertinent to digital built Britain. Turner Harris also note the lessons to be learned from the manufacturing sector in technologies such as Product Lifecycle Management and Enterprise Resource Management (*ibid*., p. 35).

As well as the lessons to be learned from other sectors, sequencing within the sector will support learning. Careful prioritisation might enable high-value / high-consequence parts of infrastructure to act as proving grounds for some aspects of digitalization before rolling it out to other parts of the industry later. For example, Turner Harris identify the opportunities in Context-sensitive Hazard Management & Monitoring, noting their likely uptake first in assets of greatest value and sensitivity (*ibid*., p. 41). In another example, some major airports are able to deploy small-scale digital service innovations as pilot projects, which can then be expanded if successful (James, 2017). This model can span sectoral boundaries as targeted and sequenced pilot projects can represent excellent value for money.

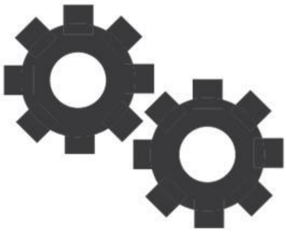
A potentially valuable practice from other sectors lies in work where there is consideration of the sector as an ecosystem, recognising interdependencies. An example of this in practice is recognising the potential for security risks to translate into safety risks, and the need that every organisation, 'Should be a "good citizen" with regard to cyber security in order to minimise the safety risks to users of transport systems and society as a whole' (Bloomfield et al, 2018).

Generically then, sector leaders and managers need to be able to seek out the experience of other sectors, identify what can be generalised, what needs adapting before transfer, and what is specific and unique to the other sector and will not transfer. In this last case, it is often possible to identify when lessons will become transferable (price points, skill levels, industry alignment) and then act as appropriate to make the conditions ripe for lessons to be relevant.

Box 8

The EU funded MATES project (2018-2021) seeks to address drivers of change in the maritime industry, primarily shipbuilding and offshore energy, that require digital skills and capabilities. They plan to do this by delivering a series of pilot studies to validate their skills strategy, engaging with industry and encouraging new entrants into the maritime sector through outreach. According to their site they plan to 'spread an updated image for the maritime industry and send out a convincing message concerning the high-tech and long-term future of the maritime sector' (MATES, 2018). Expected outcomes include a plan for dealing with skills shortages, 'greater alignment of industry needs and occupational profiles with training and curricula' and 'validation of training and education pathways for effectively increasing employability and career opportunities.' This initiative aligns closely with CDBB's change agenda for the built environment and so the outcomes of this project are worth watching.

CONTEXT: Manage digital built Britain to best respond to drivers, trends and events



The introduction below provides an overview of the **Context and drivers** category of the Capability Framework for creating a digital built Britain.

Click here for an introduction to the **Capability Framework** as a whole, including links to all the categories involved.

Context and drivers

Manage digital built Britain in response to external drivers and trends

- Detect changing drivers, trends and events that might impact the built environment (C1)
- Characterise the probability and severity of trends and events (C2)
- Predict likely impacts and identify response options (C3)

Introduction

Digital built Britain will exist in a context of external trends, drivers and events such as climate change, demographic shifts, economic cycles and natural and man-made disasters. Some of these will turn out to be 'gamechangers' (ARCC, 2016, p. 14) while the significance of others will wax and wane. The UK will need to develop the capability to discern and monitor such trends and drivers in order to predict their impact on the built environment.

To navigate this complexity, we need to consider what frameworks we should use to explore both the social and economic impact of these factors. We need decision-support tools and digital models so practitioners can work together to develop a more accurate picture of the world, predict the impact of these drivers or events and manage accordingly. This relies on better insights from high quality data, and improved models that heed uncertainty and enable planning for different scenarios of both slow and rapid change.

The wider context is huge in scale and scope and there are many important factors that are outside our control. While we may not be able to control the context, we need to be aware of it and develop the capabilities to manage the built environment in response. This section articulates the capabilities needed to make decisions in the face of dynamic and potentially unpredictable conditions that will impact the built environment, services and their stakeholders. The underlying philosophy of approach espoused here is that of adaptation pathways and adaptive policymaking (Buurman & Babovic, 2016). Such techniques are particularly suited to handling deep uncertainty while also making good use of available data and digital modelling tools – all of which are likely to be required when managing the impact of trends and drivers on digital built Britain.

The starting point will be to discern the emergence of new threats and opportunities as well as changes to those of which we are already aware. We then need to understand how the trends, drivers and events might impact digital built Britain and decide what elements are manageable, and how and when to manage them. From these elements the policymaker can prepare a programme of action which can be carried out as required or adapted if necessary.

There is, of course, a massive potential list of trends, drivers and events and every discipline will approach the uncertainty involved with different assumptions and priorities (Riesch, 2013). The key is to build generic capabilities and then to adapt these for more specialised application. This document goes into details only in terms of examples, and further examples are explored more in a supporting document (Sector Perspectives).

It is worth noting two different types of phenomena that we need to consider. The first are those that are essentially inevitable and for which the paths are largely predictable. The fact of climate change and evolving social demographics are good examples. While the degree of change is debated, we understand that the planet is warming and that there will be symptoms, such as sea level rise. This may influence the materials and design used in the built environment and determine where it is possible to build. Other parts of the world are already seeing extreme effects of climate change such as drought, famine and flooding, creating refugee crises that will only worsen over the coming decades. This may lead to demographic changes in the UK, for which urban planners need to be prepared.

The second kind of phenomena are those that will happen, or are likely to do so, but we do not know when or where – or what the magnitude of their effect is likely to be. Examples include economic shocks and natural or man-made disasters. Extreme weather events exacerbated by climate change are likely, for example, but knowing where and when they will occur is considerably more difficult. However, we can predict their characteristics and we can take some pre-emptive action. The insurance industry is experienced in this area.

Where unpredicted changes or unintended consequences arise, the resilience of the system will be tested, so although we cannot hope to manage all potential drivers, we can (and should) design the built environment and its services to be adaptable. Preparing for an uncertain future requires action plans, clear chains of responsibility and joined-up monitoring and modelling. It is also important to remember that the decisions and actions are taken in the context of societies and organisations with power structures, boundaries and scales that shift over time. To support decision-making, we must understand and include in our process models – if not in our digital models – the context in which the decision is being made, not just the context it is being made about.

This capability category is primarily interested in what drivers mean for the management of the built environment. Data and information, together with good models and decision-support tools could enable better decision-making about the built environment in ways that help deliver desired outcomes, minimise the risks and benefit the nation. However, this will be no simple feat: 'A civil engineer must work seamlessly across disciplinary silos to embrace social, environmental, political and cultural perspectives, with an appreciation of their languages and methods of working' (Rogers, 2018).   Uniting stakeholder perspectives on risk, desired outcomes and investment is complex, but digital tools and frameworks for collaborative decision-making may help. It is crucial that digital tools and frameworks take a supporting role, 'to aid decision-making, not to make decisions. They remove no responsibility from the engineer, but prompt wider thinking of the civil engineering intervention in the context in which it is expected to perform.' (Rogers, 2018)

C1 Detect new and changing drivers, trends and events likely to impact the built environment

The initial challenge is to identify the potential drivers, trends and events that may impact the built environment. In most cases there will be a handful of obvious candidate drivers: in flood-prone areas, predicted rainfall, drainage and sea level rise predictions may change how land is used and what defences are built; in cities, demographic change could dramatically alter the quantity and types of housing required; in formerly industrial regions, economic pressures may lead to difficult decisions about how the local government allocates resources for the built environment. Even the obvious candidates can impact the built environment in unforeseen ways and there may be drivers that we do not recognize as such until it is too late. Even if we cannot accurately predict the future, we still need to plan the built environment that delivers the best value with the best information we have. Therefore, identifying new and changing drivers is essential to delivering value in digital built Britain.

Today this is supported by extensive foresighting activity, both from government bodies and from commercial organisations. There is a wide market in forecasting 'megatrends'. Some of this is specifically targeted on the built environment, for example the UK government's Foresight project on the future of cities[107] and the Public Services International Research Unit (PSIRU) research into global trends and policy responses (Lethbridge, 2016). The World Economic Forum tracks potential drivers of change to employment and economics (World Economic Forum, 2016b), while the UK Government Office of Science (GOS) engages in foresight activities to predict trends that will impact policy.[108] The practice of identifying drivers and trends to aid decision-making and assessing performance relative to predictions is relatively common at macroscopic scales, and digital built Britain will benefit from continuing to develop, improve and refine it, including at a more granular level. In particular, foresighting and urban planning would both benefit from a more aligned approach, wherein foresight experts benefit from greater appreciation of the dynamic and complex nature of the built environment, and planners and civil engineers have a better understanding of socioeconomic trends (Fernandez-Guell & Gonzalez-Lopez, 2014).

Drivers and trends exert continuous – albeit dynamic – pressure on the built environment. Events, on the other hand, are a bolt from the blue, suddenly shifting the context of built assets or services. ICT infrastructure is vulnerable in different ways than other built infrastructure. A report published by the UK's Office of Science Infrastructure and Resilience (Guthrie & Konaris, 2012) identified several specific vulnerabilities that could affect the fundamental infrastructure over which digital built Britain will work in a changing climate and threat landscape:

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[107] http://www.gov.uk/government/collections/future-of-cities
[108] http://www.gov.uk/government/groups/futures-and-foresight

- While physical infrastructure may be hosted locally, data transfer and storage may take place internationally. This can make UK infrastructure vulnerable to entirely different natural and human threat events.
- Extreme weather events and rainfall can flood underground ICT infrastructure, damage over-ground infrastructure and prevent access to damage sites for repair particularly in the case of heavy snowfall.
- Spiking temperatures are likely to cause overheating in data centres and base stations and influence the distance wireless signals can transmit.

A critical event to plan for and understand in a wider context is a Black Sky scenario. These are characterized by catastrophic and enduring power failures, with knock-on effects to critical infrastructure and services. A recent extreme example is from Puerto Rico, where power was out or unreliable for over six months after Hurricane Maria, leading to widespread medical, food and water crises as the 'system of systems' reliant on the energy grid ground to a halt.

In the UK, Black Sky events are more likely to come from a malicious attack than an extreme weather event, but the effects could be equally devastating, with transport, food, water, hospitals, communication and other critical sectors reliant on the energy grid, and a small defence sector that would need to address all of the cascading crises at the same time. Restarting the grid could take up to seven days, even if there is no damage to the energy infrastructure itself. Ironically, the very interconnectedness that many feel will protect us from such scenarios may make us more vulnerable to them (Electric Infrastructure Security Council et al., 2018). Regardless of probability, resilience to systemically catastrophic events such as this need to be considered in the design of our digital and physical infrastructure.

Identifying, characterizing and assessing the probability of events is the stock-in-trade of the insurance industry, and there is considerable activity and practice in doing so, from research into catastrophic risk, for example at the Judge business School's Centre for Risk Studies,[109] to the forecasting of financial impacts. As with predicting trends and drivers, better data and information about events will improve probability models and help decision-makers understand what resources are needed to plan for them. In many cases, designing flexible, resilient systems against one type of event will help with others.

C2 Characterise the probability and severity of trends and events

There are three components to understanding the potential for drivers and events to influence digital built Britain. Firstly, there is the quality of our understanding and the nature of our grasp of the uncertainties surrounding the phenomena. Then, there is the need to prioritise based on an understanding of the potential magnitude of the impact, and how that relates to likelihood. Are we, for example, discussing rare events which will have massive consequences, relatively frequent events of moderate consequence, or is the trend going to happen inevitably with predictable

[109] http://www.jbs.cam.ac.uk/faculty-research/centres/risk/

magnitude and timing (such as with an aging population)? Finally, there is the matter of vulnerability and what can be done to mitigate and manage consequences.

While it is impossible to foresee exactly when and where disasters will happen, they often have predictable impacts: flooding will damage properties and threaten infrastructure in particular ways, fires will spread or be contained based on the situation and the options for intervention. Planners can use past experiences and data to model discrete events and their potential trajectories as they unfold. Probability insights are also often available, either in absolute terms or related to severity.

Before moving into identifying and modelling uncertain futures, practitioners should have a working understanding of uncertainty. Riesch (2013) offers a view that encourages model-users to explore the sources and extent of uncertainty:

1. 'Uncertainty about the outcome', or classic probability, in which the 'model' (i.e. the decision-making context or problem) and its variables are known, but there are several possible outcomes, analogous to rolling dice. This is easy to model because there are finite outcomes with predictable frequencies.
2. 'Uncertainty about the parameters', where the model is known but the parameters are not. More information could be gathered to turn this into a simple probability problem. Resolving this might be about getting better information, or maybe the parameters are probabilistic.
3. 'Uncertainty about the model', where it is unclear which model's interpretation of reality is the 'best' in some sense. This is likely to be a source of debate among experts and hence a further challenge to the decision-maker.
4. 'Uncertainty about acknowledged inadequacies and our implicitly made assumptions.' It is here that we encounter questions about the quality of our understanding of the underlying science, the risks of extrapolation and the choice of simplifying assumptions – both explicit and implicit.
5. 'Uncertainty about unknown inadequacies: We do not even know what we don't know.' While this category of uncertainty is inherently impossible to predict, Riesch alludes to different disciplines' approaches to coping with this category of uncertainty.

This, then, is one way of exploring and communicating the various types of uncertainty with which models and decision-makers must deal. Digital built Britain is made up of complex, interlinked systems and so there will be each of these kinds of uncertainty present. Furthermore, as we explore the potential future impact of trends, drivers and events, again different degrees of uncertainty will emerge in different facets of the issues. Finally, decision-makers and planners must be careful in thinking through interacting models with different intrinsic levels of uncertainty. See also the discussion of decision-making (G5).

Modelling this complexity is a significant undertaking and new tools are being explored. While energy providers are exploring the application of soft computing to model uncertainty of dynamic systems (Molina-Solana et al., 2017), the National Infrastructure System Model (NISMOD)[110] and Data and Analytics Facility for National Infrastructure (DAFNI) project[111] have developed the UK's

[110] http://www.itrc.org.uk/nismod/
[111] http://www.dafni.ac.uk/

first national infrastructure 'system of systems' modelling tools and platform. This enables the modelling of lifetime performance of infrastructure, as well as risk and vulnerability, the impact of infrastructure on local development and other related factors.

Such capabilities and the underpinning research and tools are profoundly important in producing useful insights that can help decision-makers understand future scenarios and plan accordingly (Blainey & Preston, 2019). (See also the topics around complex integrated systems in section G4). Colace et al. (2018) demonstrate that information exchange over mobile networks opens up new capabilities to model and predict critical events by understanding the relationships between dimensions such as weather, crowd behaviours and traffic patterns. They use a Bayesian Network to deal with the uncertainty within and between these dimensions. While this type of interoperability is difficult, political and social will, a guiding vision and investment will enable the development of technology that will support better predictive modelling of multiple factors in the built environment.

Determining the probability of drivers and events is vital to ensure that resources such as time, effort and money are spent most effectively. Probability in such dynamic and interconnected systems as the built environment is difficult to calculate, but government and insurance sectors have developed systems and calculations to understand the likelihood of various scenarios. Policymakers can consult guidance on foresighting to understand how to prioritise attention and funding allocation (Government Office for Science, 2016b), and scientific research has an important role in policymaking by providing the evidence that helps inform these foresight activities (Centre for Science and Policy, 2019). In the property insurance sector, for example, risk-based insurance pricing uses the most accurate available flood risk predictions to price insurance relative the risks (Hudson et al., 2016).

To continue with the flooding example, academic research continues to make major contributions (Centre for Ecology and Hydrology, 2019) to predictive modelling capabilities (e.g. Skinner et al., 2015), and our ability to model and predict flooding is constantly improving (Trigg et al., 2016), while the government has produced guidance on how to conduct flood risk assessments for planning applications (Department for Environment, Food and Rural Affairs, 2017). However, given the value of accurate prediction, there is a risk of data and models being used as soon as they are produced without adequate checks, leading to credibility problems (Trigg et al., 2016), demonstrating the importance of confidence in data quality (D1) in modelling these complicated and complex systems (G4). Building this confidence is also discussed in the section on decision-making (G5). Despite our ability to fairly accurately model short-term flood risk, there is work to be done to estimate the investment level needed for long-term flood and costal risk management. The National Infrastructure Commission (2017a) identifies the need to explore how government and the water industry can take a longer-term, more joined-up perspective on flooding, drainage and sewerage to stay ahead of risks. This will need to be done by means of digital sensors, modelling and integration. The successes and failures in developing a built environment that is resilient to flooding provides a useful case study when considering the UK's approach to similar events.

Modelling does not just rely on sensors and historical data. Increasingly, citizen science and participatory methods are used to improve predictive models. Biodiversity, conservation and water quality modelling have benefitted from contributions by citizens for years. Now, real-time, crowd-sourced data on pluvial flooding could lead to a more granular understanding of where and when water levels rise (See, 2019). However, engaging citizens, particularly after a flooding event, comes with a number of caveats: that the loudest voices may not be the most knowledgeable, that timing data collection matters, and that, 'where participants have limited technical and/or numerical capacity, very high levels of conceptual and numerical simplification must be applied to the representation of the local flood risk system if the participatory model is to be accessible and meaningful to the participants that develop it' (Maskrey et al., 2016).

It is difficult to draw broad conclusions given the range of ongoing research and applications work in assessing likelihoods for drivers and events. Much of the work focuses on disaster prediction, management and recovery; emergency response systems; and mathematical or computational methods for predicting risk in dynamic systems. Another body of work addresses contracts, insurance and supply chain management in the face of uncertainty. Academic and practical work on modelling is going on in partial isolation, such that food supply, climate, crime, energy use, demographics and economics all benefit from increasingly robust predictions. However, interdisciplinarity will be key to integrating these strands to create an integrated understanding to underpin decision-making.

No matter the method used to model probable futures, it is vital that foresight activities are based on concerns, drivers and outcomes that are relevant to all stakeholders. 'Whilst urban foresight tools offer a useful way of developing a city vision, there are critical questions to resolve, including, who is the vision for? and, who leads (and owns) the vision?' (Dixon, 2018) This ties back to negotiating and defining value (V1) as the basis for targeting the exploration and modelling of trends and events.

A separate branch of futures thinking addresses the scenarios that pose an existential risk to humanity, effectively threatening our survival as a species, see for example the Bulletin of the Atomic Scientists[112] and the Cambridge University Centre for the Study of Existential Risk[113]. This academic discipline is influential in warning about the hazards of artificial intelligence and climate change, among other existential threats that researchers, decision-makers and citizens should heed. However, the probability of these scenarios is relatively low. While the possibility of catastrophic futures should encourage responsible decision-making, it is not explored further as a research domain here.

C3 Predict likely impacts and identify response options

With a system in place to detect new trends, drivers and candidate events, and with an assessment of the magnitude of the opportunity or risk (i.e. of likelihood and magnitude), attention turns now to the need to act where possible and where appropriate. If action now is not possible or appropriate then the questions arise: what can we plan to do, when should those actions be triggered, and when

[112] http://thebulletin.org/
[113] http://www.cser.ac.uk/

might we wish to change our plans in light of changing circumstances? These are explored here in pursuit of building the capability to discern and plan appropriate action:

- Develop approaches and tools for choosing what to do and when (C3.1)
- Customise approaches and plans in the light of extant domain insights (C3.2)

C3.1 Develop approaches and tools

Given the impossibility of long-term forecasts that will be sufficiently robust to guarantee that a given policy can remain unchanged, promising policy directions can be seen in 'adaptation pathways' and 'adaptive planning methods' (Buurman & Babovic, 2016), drawn in large part from climate change mitigation work. Therefore, in exploring this aspect this document draws upon the philosophy of adaptive planning methods and the analogies that may be drawn from such work and applied here. Reviews of such approaches can be found in Bakshi, Talaei-Khoei & Ray (2013) and Walker, Haasnoot & Kwakkel (2013). Component tool sets are explored by Swanson et al. (2010). Such approaches make considerable use of data to indicate evolving pathways and models to predict candidate futures and their mitigation or management options. Hence, such an approach seems well-suited to the attributes of the envisaged digital built Britain and the tools that will enable it. Research to explore this would be potentially useful.

One example of intervention planning under deep uncertainty, in complex contexts and over long timescales is the Thames Estuary Plan (TE2100), which uses predictive models for sea level rise and climate change scenarios to prioritise planning policies, land management and interventions along the Thames through the year 2100. According to David Wardle's introduction, 'Our Plan is needed to provide confidence to those who live and work in London and the Thames estuary area that flood risk is understood and is manageable. Planners and investors will be reassured that there is an effective plan to manage flood risk today and for future generations.' (Environment Agency, 2012) The approach taken here has been described as seeking 'dynamic robustness', building flexible strategies that can be changed over time as more is learnt or as conditions change (Ranger, Reeder, & Lowe, 2013). They identify key aspects of the 'decision-centric' process as combining numerical models and expert judgement to develop narrative sea level rise scenarios, the use of the 'Adaptation Pathways' approach and the creation of a monitoring framework that triggers defined decision points. This seems a good example of a generalisable approach.

The development of platforms to allow integrated modelling using data sets of known and managed provenance will be another foundation stone here. A prime example of such a platform is the Data Analytics Facility for National Infrastructure (DAFNI).[114]

A selection of considerations for response approaches are discussed below:

i) Sets of indicators
ii) Scenarios and their use

[114] https://www.dafni.ac.uk/

iii) Interaction
iv) Evaluation and learning

i) Sets of indicators

Work has been done on identifying what makes a good set of indicators, albeit in the environmental context (Bossel, 2001; Niemeijer & de Groot, 2008), but such work could be translated and adopted to other purposes for the management of the built environment. This work in the environmental sector has noted the need for explicit criteria for good sets of indicators, a portfolio to allow more robust interpretation and, importantly, a causal network that explicitly captures the mental and computer models being used by researchers. This thinking draws heavily on the discussions about interlinking cause and effect, both in general (V1) and specifically to services embedded in the built environment (S2), about the development of integrated and interacting systems (G4), and about the use of models in decision-making (D1). The key attribute sought in developing a set of indicators is their ability to mesh with models to build a better understanding of the reality that policymakers and decision-makers face within the contexts of interest. Work has been done in developing indicator sets that relate explicitly to the built environment, for example for sustainable development (Winston & Pareja Eastaway, 2008) and for urban health (Pineo et al., 2017). Care needs to be taken about whether such indicators are regarded as signalling precursors or signalling outcomes.

Indicators developed by the NHS include: ‘Preventing people from dying prematurely’, ‘Enhancing quality of life for people with long-term conditions’ and ‘Treating and caring for people in a safe environment and protecting them from avoidable harm’ (NHS England, 2019). Such indicators are a mix of precursors and outcomes, needing a contextual model to underpin decision-making. Similarly, many of the UN indicators for the Sustainable Development Goals (SDGs) could be adapted carefully, again with research to be done to identify the causal models to underpin decisions (United Nations, 2018a). The UK government has committed to the SDGs as a yardstick for sustainability, economic wellbeing and development (Department for International Development, 2018). There are entire catalogues of data to underpin sets of indicators and the domain is well supported.[115]

There is a need to understand the trade-offs and descriptive limits of these indicators, however. ‘Great care is also needed in developing indicators of benefit: in the short-term human well-being may often increase through the destructive and unsustainable use of biodiversity.’ (Sparks et al., 2011) Discussion and consensus is needed on both the validity of the underlying cause and effects in action and on what trade-offs can and should be made between different stakeholders, including the natural environment. As with critiques of the SDGs, indicator sets are necessarily indicative and may contain blind spots or false equivalences (Hickel, 2015). This suggests research to explore which indicators would be most appropriate for digital built Britain in various contexts.

For example, sets of indicators for digital built Britain might then dovetail with existing metrics for social demographics, economic equality, digital engagement, economic performance, climate, disruptive technologies and political structures. Each of these aspects will interact, so cross-coupling

[115] See http://www.eea.europa.eu/data-and-maps/indicators and http://www.eea.europa.eu/data-and-maps/indicators/about

between them will be needed and attention should be paid to the consequences of any simplifications that are necessary.

Within adaptive policy frameworks, some indicators have 'trigger values' which then initiate actions, appropriate interventions and an exploration of new policy options if needed. The use of tools such as these has been explored (Raso, Kwakkel, & Timmermans, 2019), and could potentially be applied to the decision-making and policymaking processes for digital built Britain.

ii) Scenarios and their use

The impact of drivers depends on the specifics of the context, making prediction difficult, even with digital data modelling. Models designed to show a single outcome need to be revisited in the face of multiple potential future trajectories. Therefore, human decision-makers may need to sort through an array of possible futures based on a mix of quantitative and qualitative evidence. Scenarios can be assessed, often in combination with models, to develop insights and to explore candidate options for action and intervention. Scenarios are a rich method for understanding the impact of drivers and trends as they enable a narrative approach to problem-solving using qualitative information.

Scenarios can be generated by human decision-makers, through participatory studies or guided by digital models. In the case of NISMOD, scenarios were used to explore future states beyond the ones deemed most probable. This exploratory approach considered factors for which there were management and policy options that might influence the outcome, and factors beyond the control of decision-makers (Blainey & Preston, 2019). Creating scenarios can guide thinking, but are not a solution in and of themselves (Rogers, 2017). There are various ways of deploying scenarios in future thinking, but it is important that they are deployed appropriately, with due rigor.

Establishing consistent and rigorous use of scenarios within decision-making (G5) requires further exploration (Uncertainty, section 2.9).

iii) Interaction

The other complicating factor is that the trends and drivers are interlinked and interacting, so it will never be enough to consider any driver in isolation. UIL illustrate how climate change, economics, demographics will all impact the transport sector simultaneously, making its resilience ever more important for the UK, especially as it becomes more tightly coupled to other sectors in the UK (UIL b, pp. 9, 18). Similar interactions can be drawn out the domains of education, energy and healthcare (UIL a, section 2). Increasing affluence, population density, and integration are all contextual drivers with the potential to magnify the impact of natural disasters, and these trends will continue (Etkin, 1999). The management of digital built Britain will have to build the ability to consider the interaction of multiple drivers in different combinations and in different sectors in order to identify and address implications most effectively (see Sector Perspectives).

iv) Evaluation and learning

For every decision about where and what to build, how and when to maintain, what and how to monitor, there is a set of dependent decisions. Decision sets describe the problem statements and trade-offs that decision-makers need to navigate, whether or not they are aided by digital tools. Each decision in the set may have knock-on effects, unforeseen costs and unexpected benefits. Mapping these decision sets and learning from past experiences can help predict what these impacts are likely to be.

However, Shahab, Clinch & O'Neill (2019) assert that evaluations of planning decisions all too frequently exclude unintended impacts. Instead, they focus on whether the results conform to expectations, and only look for evidence that supports this conformity. They propose an impact-based approach, including an exploration of acceptability – 'the degree to which the design and implementation of a policy is supported by affected people (social acceptability), as well as decision-makers (political acceptability)' – and effectiveness – 'the degree to which the objectives formulated in policy instruments were achieved or are expected to be achieved'. Rather than checking boxes that an asset conforms to technical expectations, they suggest evaluating assets based on whether they deliver desired outcomes and are acceptable to a wide range of stakeholders (see VALUE).

Review of past events and outcomes offers opportunity to review decisions made, within given policy contexts and thus to learn. Creating a taxonomy for evaluating foresight projects (Fernandez-Guell & Gonzalez-Lopez, 2014), sharing successes and failures of emergency planning and response and reflecting on how data supports decision-making will contribute to the UK's capability to learn from previous experience to better manage the built environment in the face of drivers, trends and events. Such reflection on past events and emergencies (e.g. Royal Academy of Engineering et al., 2016) will help ensure inclusion of stakeholders, exploration of real outcomes and can build engagement with the whole process by which policies and decisions are made. (See also the section discussing the communication of decision contexts and outcomes, G5).

C3.2 Customize to use domain research insights

There is a wide range of possible domains that could be impacted by decisions about the built environment, including biodiversity (Opoku, 2019); climate, microclimate and urban heat islands (Soltani & Sharifi, 2019); human health and wellbeing (Bird et al., 2018); crime (Armitage, 2017); and economic growth, to name just a few. Balancing the impact of the built environment on all of these contexts – and vice versa – can seem daunting, but in many cases the design principles that support each one align, for example green spaces supporting wellbeing and the environment (Hiscock et al., 2017). There is a growing body of literature in this area and working toward a valid framework for decisions that contribute to agreed outcomes (V1) would be beneficial.

The following pages explore some of the specifics of different trends, drivers and events:

i) Emergencies and cascades of failure
ii) Environmental changes and pressures
iii) Demographics

iv) Economy
v) Political changes
vi) Cultural norms and societal behaviour
vii) New technology

i) Emergencies and cascades of failure

The emerging capabilities of data, information and digitalization may offer new options for response to emergencies. These are, of course, already topics of research (e.g. Alazawi et al., 2014). New modalities of detection, of monitoring and of response can be fitted neatly into the topics discussed above. Much of the smart disaster management literature focuses on earlier detection and how to maintain connectivity and communication in disaster situations (e.g. Khan et al., 2019). Other articles focus on smart devices for recovery efforts, such as remote vehicles (robots, drones, etc.), or sensor-enabled helmets and body armour for rescuers (Jeong et al., 2018). Emergency response planning is done by national and local government and can be seen in documents such as the Civil Contingencies Act (2004) and its accompanying non-statutory guide (HM Government, 2013).

The UK's Government has Sector Security Resilience Plans (SSRPs) for each UK infrastructure sector. Those documents are classified, as they contain sensitive information about the programme of actions for achieving the desired level of resilience and methods of reporting on progress. Additionally, it maintains a National Risk Register[116]. Fire, flooding and terrorism emergency procedures have all been tested in recent years, and most organisations will also have disaster plans, drills and clear chains of command.

However, these plans are put to the test when emergencies cascade, as in a Black Sky event. Brian Collins describes these scenarios as follows:

> *'Black Sky is about the unthinkable situation of everything failing. Most of you will have worked on disaster-recovery plans, business-resumption plans, which assume that some supporting services are intact after the event. This is about challenging every one of those assumptions. Whatever you assumed was going to work in order that your disaster-recovery process could be booted or started up, that assumption is invalid. That's what we mean by Black Sky.' (Electric Infrastructure Security Council et al., 2018)*

Researchers, such as the Cascading Disasters Research Group at UCL, have produced articles (e.g. Gianluca Pescaroli & Alexander, 2016) and guidance (e.g. Pescaroli et al., 2017) for emergency planners, and disaster plans for built assets should include contingencies for major 'what if's'. What if ICT infrastructure fails and people cannot communicate with emergency services? What if power is out for an extended period of time? The government's sector resilience plans also emphasise the need for back-up power and multiple redundancies (HM Government, 2017).

[116] http://www.gov.uk/government/publications/national-risk-register-of-civil-emergencies-2017-edition

The cost of failure in planning for or responding to emergencies can be dramatic. Whether it is the lack of investment in the flood defences in New Orleans (Fischetti, 2001) or the response to the Grenfell Tower fire (Taylor, 2018), emergencies that result in the loss of life or significant cost often come home to roost for policymakers, who have learned in the backlash after these events that response behaviours matter. 'The behaviour of individuals, businesses and government entities before, during and right after a natural disaster can dramatically affect future impacts and recovery time.' (Surminski, et al., 2018) Interdisciplinary research could usefully explore such relationships and the many ways that digitalisation and wider availability of data might impact actions and outcomes.

In emergency response, then, an important facet of response is human behaviour, including empathy that crosses gulfs of implicit bias (Cuddy, Rock, & Norton, 2007), and results in a fair and just recovery process. There may be a role for technology in overcoming these gulfs. For example, MIT's Deep Empathy programme is developing AI technology to show people what their own neighbourhoods would look like if they were hit by far away disasters or wars[117]. Similarly, digital decision-making systems could be designed to ensure that recovery response is distributed justly across emergency victims. Fair machine learning (ML) is a growing discipline where multiple methods are being cultivated in an attempt to make AI more just. However, efforts to be statistically or algorithmically just, 'can often harm the very groups that these measures were designed to protect' if not done carefully (Corbett-Davies & Goel, 2018). Fair ML must be implemented by developers who have justice as a core design principle (Coulton, 2013), and be deployed and evaluated in conjunction with human practitioners to ensure that recovery from disasters and emergencies is conducted equitably.

ii) Environmental changes and pressures

One of the largest drivers of change as we transition to a digital built Britain is climate change, and its symptoms of extreme weather events such as flooding, drought and windstorms. The ability to forecast and model changes to the environment will be of paramount importance for decision-makers, and a great deal of work is ongoing worldwide to help us achieve this. Knowing where and how to build, how to defend against and recover from climate related events and how to minimize our impact on climate are key to managing the built environment successfully in the face of this inexorable set of circumstances. Because this domain has so many potential contributors, resources such as the UK's Green Building Council's map of actors and resources[118] provide signposting.

Forecasting weather and climate take place on very different scales. A wide range of industries rely on accurate weather modelling, including energy, transport and logistics, on which the built environment relies. Predicting future climate and weather patterns is also increasingly important as the jaws of climate change begin to bite. The National Oceanic and Atmospheric Administration (NOAA) in the USA, the Met Office in the UK and the European Organisation for the Exploitation of Meteorological Satellites are just some of the many public and private bodies that track and model

[117] http://deepempathy.mit.edu/
[118] http://www.ukgbc.org/ukgbc-work/climate-resilience-actor-and-resource-map/

climate to provide early warning for hazardous weather events and from which climate predictions are extrapolated. These organisations and others are continuously developing their modelling and foresighting capabilities, enabling planners to have a better idea of how best to invest to protect built assets and the people who use them.

Planning for future climate hazards happens on a local level and varies across the country and there are particular areas at higher risk than others (Environment Agency, 2019). However, local risk assessments also need to consider systemic effects, such as how upstream water management might impact flood levels in a city centre (Environment Agency, 2016). In some cases, the most effective defence might be to build or maintain infrastructure (levees, drainage channels, etc.), while in others it is to allow the natural environment (planted banks, marshes, etc.) to provide defences. In still others it is an issue of educating and encouraging behaviour change in people, for example teaching farmers better methods for managing run-off from fields. The best defence against future hazards is not always to build something, and that must be reflected in the decision process.

In order to predict the impact of climate change on the built environment, there exist local-scale models that perform simulations of land-use scenarios. These tools have been widely used to further understand the temperature perturbations due to land use in urban domains (Hamilton et al., 2014), to identify risk areas and to appraise the severity of future problems relating to urbanization and climate change (Virk et al., 2014). More recently, Aktas et al. (2017) looked at urban climate models to define the capacity of materials to absorb, store, reflect and radiate energy, and discuss how the land use parametrization can be improved from a materials standpoint. Modelling the various land use and material options against likely outcomes of climate change will help navigate trade-offs between investment and likely property damage. Tools have been created to signpost different initiatives looking at climate resilience in the built environment, for example the UK Green Building Council's interactive tool, 'Climate Resilience Actor and Resource Map'[119].

Preventing flooding and other such disasters is not simply an issue of property damage, loss of business revenue and staff time. Weather-related disasters can take a psychological toll on those who experience them, meaning that flood risk management has benefits to health and wellbeing that could change cost benefit ratios if included in the assessment. The Environment Agency recently used this method and increased the benefit cost ratio from 16:1 to 24:1 as a result (Environment Agency, 2019). Such insights relate also to the wider questions of making digital built Britain investable (V3).

In addition to flooding, air quality and drought are two major factors in the environmental context of the built environment. Various studies are currently using modelling technology to better understand these problems. In urban areas, air quality is a growing concern, as poor air quality is known to affect human health (World Health Organization, 2016) and a case study developed at the London Heathrow Airport using a network of low-cost sensors created a powerful predictive tool for pollutant concentrations in and around the airport, separating off local and non-local emissions (Popoola et al., 2018). Drought Risk and You (UWE Bristol, 2019), aims to develop an easy-to-use

[119] http://kumu.io/embed/c456c9cf88be97e13a9ccec7c1c459e1?settings=0

tool for drought risk management. Among other themes, they plan to examine the influence of rainfall, water levels and temperature on drought perception as well as to explore the impact of policy decisions on drought management. Additionally, they study how local knowledge relates to synergies and trade-offs in water-use conflicts. Extending this type of research, using new sources of data and tools for analysis – and linking it with other potential drivers – will help us better understand the dynamics of air pollution, drought, and other climate-related hazards in order to predict the needs for and timing of interventions.

Recovery from extreme weather events in the built environment can be aided by digital technology as well. As discussed above, digital technology can help ensure rescue and recovery efforts are safer and can also help communities recover long-term through participatory design projects. For example, researchers developed an interactive model of a borough of New York that was heavily impacted by flooding after Hurricane Sandy in 2012 and allowed residents to model their own preferred scenarios for future flood resistance urban design and development (Giampieri et al., 2019). Insights from projects like this could feed into decision support tools so that more stakeholders have a say in how their community is protected from similar events in the future.

Climate change has the potential to exert a profound influence, not only through catastrophic events and slow but obvious mechanisms such as rising sea levels and consequent flood risk, but also through more subtle mechanisms such as carbonation and chloride penetration damaging concrete, increasing corrosion of structural components, and increased solar UV levels. These effects need to be considered within the resilience agenda. Cerè, Rezgui & Zhao (2017) present a framework for thinking about these consequences.

Cerè et al. (*ibid.*) highlight four areas requiring further research toward more resilient buildings: (1) risk-based, cost-optimal resilient design of buildings and infrastructures, (2) model-based evaluation and optimisation of buildings and infrastructures, (3) integrated risk modelling, inference and forecasting, and (4) heterogeneous disaster data acquisition, integration, security and management. Ultimately, the built environment of the future needs to be modelled and managed as a ‘system of systems’ that includes all the infrastructure required to maintain the resource nexus of water, land and energy, as well as the contribution of this infrastructure to the greenhouse gas emissions that drive climate change (Konadu et al., 2017).

iii) Demographics

Planning for the built environment of the future demands knowing what people will need, which in turn is determined in part by the types of people living there. However, modelling to predict future demographics is challenging. The Office of National Statistics gathers data on the UK population and uses that data to check its own projections, leading to better modelling and forecasting of demographic trends (Office for National Statistics, 2018a).

Statistics and projections show that the population of the UK is aging and will continue to age, with the potential for an additional 8.6 million people aged 65 or older over the next 50 years (Office for National Statistics, 2018b). This demographic shift will have implications for the needs of the built environment, economy and workforce. Will people work later into life, and if so, in what sectors?

What social and healthcare programmes are needed to support this growing population and what will be the implications for social infrastructure and services? What will happen to the housing market for young and old alike and what technological or social support will be needed in homes? According to the ONS, 'Public and private transport is less available in rural areas than in cities, so people are more reliant on cars but driving rates decrease with age. This can leave older people in rural areas isolated and struggling to access services, particularly those who cannot afford to pay for taxis or do not have family members or neighbours who can provide transport.' (Office for National Statistics, 2018b) How can transportation and service design help combat social isolation of older adults and those with special mobility needs? Answering questions like these will help planners shape the built environment.

To give an example of how the built environment can impact wellbeing, good design and planning can help physical and social mobility, and bring about positive outcomes. According to report by the Government Office for Science (2016a), 'A well-designed built environment can maximise the physical mobility of older people, leading to increased activity levels, better health, and improved quality of life for a full range of users.' Ensuring older adults remain equipped with the digital skills and literacies (L2) needed to participate in digital built Britain will reduce their chances of isolation and ensure life-long engagement with an increasingly digital society (Government Office for Science, 2016a).

The other contributor to demographic change besides birth and death rates within the UK is migration between the regions of the UK and from other countries. While the major factor contributing to the UK's urban population boom is the overall 'natural' growth of the population, it is undeniable that over the last two decades people have been moving to cities more rapidly than they have moved out of them. The future of this trend is uncertain, however, and current urbanization patterns could just as easily reverse (Government Office for Science, 2014). Indeed, housing prices, hyper-competitive job markets, wellbeing and other factors are already driving many away from big cities like London (Tyzack, 2017). It is therefore not safe to assume a broad, nation-wide trend towards urbanization now or in the future.

Migration to the UK accounted for roughly 0.39% of annual population growth between 2001-2011, but how this trend develops in the future depends on many factors including the environment, economics and geopolitics. Gathering data about drivers for international migration can be very difficult because people's reasons for emigrating to Europe from other global regions may change over time, so a simple label does not describe how they plan to settle or what drivers determine their choices or actions. 'Predicting future migration is also very challenging and requires a detailed understanding of the factors driving migration flows, including conflict, social unrest and economic instability, which are themselves difficult to predict.' (Cummings et al., 2015) Quality information and data about migration are crucial for making predictions about future trends, but the accuracy of these predictions should not be relied upon. From a planning perspective, flexible, affordable housing and transport options with good universal design principles should help UK citizens and residents of many different backgrounds to thrive in digital built Britain.

Demographics are also closely related to social and cultural trends. The Urban Big Cata Centre[120] is doing research interrelating different social trends such as rented accommodation trends and its impacts on mobility and location choice, and hence on outcomes in education, the labour market, health and social care. Each of these factors can influence the demographic makeup of neighbourhoods, cities, or even whole regions. More research is needed to understand these relationships, how to predict changes and the role of planning and the built environment in demographic trends on the neighbourhood level up to the national level.

Another intersection worth exploring may be the impact of the design of the built environment on integration, identity and community building. For example, can urban planning help bridge divides between immigrant communities and other residents of cities?

iv) Economy

The built environment and its services are intimately linked with the fortunes of the economy, as was evident when the banking and housing markets crashed in tandem in 2007. Economists, too, are aware of the value of more and better data when it comes to predicting economic cycles. The value of developing better modelling is evident to this sector and there is already much work ongoing in this area.

Digitalisation could alter the economy by enabling new economic models (for example the circular economy and sharing economy models), new business models and new modes of working. Therefore, research might explore the potential implications of models such as the sharing economy for urban planning and policymaking (Ferreri & Sanyal, 2018). There is not much recent research looking at remote working (telework) and its potential impact on infrastructure, society and economy. From the public transport viewpoint, a particular benefit may be obtained through reducing demand at peak times, or at least reducing the need for additional infrastructure as the working population grows. Policies to encourage teleworking could work in tandem with levers such as greater variation in transport pricing by time of day.

Political changes

Politically motivated policy changes may influence the management of the built environment and digital technology. For example, if housing is the primary issue for the party in power, there will be substantial investment in that area, where infrastructure may be a higher priority to another party. Political will may shift in response to climate pressures such that the socially acceptable trade-offs change. For example, if air quality in urban areas becomes a significant issue to voters, then green spaces may become a more attractive use of land than new civic buildings.

It is difficult to predict what changes politics might bring over the next 50 years. One need not look further than recent headlines to see how political decisions can dramatically shape the investability

[120] https://www.ubdc.ac.uk/

of homes and businesses in the UK. Political favour may shift toward or away from Big Data, changing the acceptability of digital built Britain altogether. Therefore, research should continue to explore how governance and politics act as drivers for the built environment in order to understand how to manage complex projects and integrated assets through-life, across decades of political change.

v) Cultural norms and societal behaviour

How well can data about behaviour patterns describe cultural motivations, norms and expectations? This is a question that social science researchers are working through as the discipline shifts toward embracing predictive modelling. Some readily available data, for example from mobile phones, can act as a proxy for behavioural norms (Kondor et al., 2017), enabling researchers to understand more about how people in particular cultures act on a regular basis. Indeed, thanks to habit and routine, human behaviour is apparently predictable to about 70% accuracy. However, shifts arising from major changes, like the social impact of the World Wide Web, are effectively impossible to predict, while political races and other scenarios with a limited range of outcomes are moderately predictable (Hofman et al., 2017).

Big data represents an opportunity for social scientists to show the predictive power of their theories, and for data scientists to understand the 'substantive relevance of their predictions, rather than to predictive accuracy alone' (Hofman et al., 2017). Developing indicators to help describe and model human behaviour and cultural norms could go some way towards helping predict some of the needs from the built environment. This is a huge area of research that intersects with Digital Humanities, Social Sciences and other fields, and this overview cannot hope to do justice to all of the newly-opened areas of research in, about and from the built environment thanks to the insights Big Data can give us about society and culture. However, there are some interesting tools and projects in development that seek to bring social and cultural factors into the planning process.

The Tombolo project, initially funded by Future Cities Catapult, has developed a system to interconnect datasets and urban models, enabling urban specialists to create models from a wide range of data sources. This system attempts to integrate models of 'hard' infrastructure with 'soft' human-behavioural models and datasets (e.g. transport, with health, with demographics). Therefore, they can manage urban models based on information such as healthcare statistics and infrastructure to predict the impact of their policies and projects across topics such as the economy, environment and health. The final aim is to help policymakers, planners, designers and developers making better decisions based on the outcomes of this integrated modelling system (Future Cities Catapult, 2016/2018).

The Berkeley Group has created a framework to define socially successful sustainable places to be used by developers and planners. This tool[121] permits Berkeley Group to design new housing and

[121] http://www.berkeleygroup.co.uk/media/pdf/l/h/berkeley-social-sustainability-toolkit.pdf

mixed-use developments considering people's preferences in terms of links with neighbours, access to transport, feelings of safety, a positive local identity, and the ability to influence what goes on.

The Equality, Diversity and Inclusion Tool (EDIT)[122] from Mott MacDonald is an Excel-based tool that helps project managers, designers and lead engineers make evidence-based and informed decisions about their scheme, supporting the appropriate consideration of social issues in project design and development. EDIT uses scheme information, social and demographic data, current research, and the wider evidence base to identify which schemes are likely to have the greatest equality impact and therefore which schemes to target with additional energy and resources.

Developing these tools and capabilities – and a framework for evaluating them against desired societal outcomes – will help policymakers and decision-makers better incorporate an understanding of cultural and social drivers in their deliberations.

vi) New technology

Rapid developments in technology will undoubtedly shape the future of the built environment, and knowing how to proactively engage with it is the subject of much speculation from technology consultants, academics in the futurism discipline, and industry leaders. As always, horizon scanning will be a useful capability, as will having digitally literate people in key roles. Gartner predicts that smart city-enabling technology such as city operating centres, blockchain in government, digital ethics and Mobility-as-a-Service will come to maturity in 5-10 years, while general AI and fully autonomous vehicles will not hit before that timeline (Tratz-Ryan & Finnerty, 2018). These estimates are useful for planners to understand and prioritise when to invest or brace for the impact of these technologies.

However, more technology requires more infrastructure. According to the National Infrastructure Commission (National Infrastructure Commission, 2017b), there are already existing mobile connectivity challenges on UK roads. Supporting new technology in the built environment will require the provision of high quality and ubiquitous coverage throughout cities and along transport links. To achieve this on UK roads, substantial additional infrastructure will be required.

With any new technology, there are risks to adopting too early. Format wars, gaps in the standards landscape and other factors may mean that it takes some time for a 'winning' version of the technology to emerge from a crowded field, and expensive investments can go to waste for organisations or governments that back the wrong one. Therefore, proof of concept demonstrators, small-scale pilots and other minimal investment projects could help inform these decisions and ensure that investments are evidence-based.

In summary, these various contexts, drivers and trends may have a profound impact on the built environment of the UK. Research into models, plans and potential interventions covering many of them is already underway, however, so forecasters and planners in both the public and private sectors may be able to adopt and adapt such expertise as we transition toward a digital built Britain.

[122] http://www.mottmac.com/article/9312/equality-diversity-inclusion-tool

Conclusion

Digitalisation will continue to happen, whether we take efforts to direct it or not. Not only will the tools for managing and analysing data, information and models continue to evolve, but the monetary value of data is already clear, and the private sector will continue to use this to their advantage. Google affiliate Sidewalk Labs' controversial smart city project in Toronto, Canada, for example, poses an interesting example of the potential tensions between an ideal as painted by commercial supporters of a digitalized built environment and the citizens who see trade-offs they may not be willing to make (Cecco, 2019). The question, then, is how best we should intervene to use increasingly ubiquitous data and digital technology to create the many forms of value envisaged in digital built Britain: for society, for citizens, for the natural environment. Further, what capabilities are needed to do this?

First, we need to understand what kind of future we can expect with or without various forms of intervention. Disciplines such as history, economics, philosophy, social science and digital humanities can offer insights in this area. By doing nothing, markets will likely decide how and where technology is deployed. The impetus to share data will remain fragmented and existing silos are likely to deepen. Furthermore, short-term commercial pressures and measures of performance may prevail over the pursuit of social and environmental good. Individual building commissioners, planners, SMEs and citizens will lack the power to change deeply ingrained cultural norms, expectations, structures, and practices.

We need to be able to articulate the future we want and the trade-offs that personally and collectively are acceptable. This entails comparing the tangible and the intangible, the short and long term, and the inevitably unequal distribution of benefits and costs. We need to keep in mind where we want to go.

We need then to understand what types of interventions are possible, and how they can steer us away from more dystopian visions of the future and toward an equitable digital built Britain. This process cannot arise from a single policy, technology or framework, but more from many interventions manipulating dozens of interdependent variables and monitoring the outcomes. Digitalisation of the built environment can help identify and measure these interventions and outcomes, but it will always be up to researchers and decision-makers from multiple disciplines to identify where understanding falls short or where the data, information and models fail to paint a nuanced or inclusive enough picture to allow the right decisions to be made and the right interventions to be managed. Contexts will change, technologies will develop and digital built Britain will see both new opportunities and new challenges. The key is to build the capabilities to discern, to understand the situation and to create options from which the best can be chosen and developed.

For example, in a city with greater flood risk, sacrificing some potential housing stock to allow more resilience may be appropriate. Digital tools may help frame the problem, the options and the 'best' way forward. Digital services adapted for homeless people may not appeal to more digitally engaged citizens, but reducing the digital divide and including vulnerable populations may be worth the extra effort to design for a spectrum of users. Finally, investing in data interoperability will cost money in the short term, but may unlock new forms of value in the future. We need to develop the capability to find those sources of value, to map out the ways to get there, and to then take the pragmatic actions necessary – and each of these can build on digitalisation and new capabilities. We need also to manage the downsides. We need to be alert to risks, especially around security and privacy so we will need the capabilities to manage the threats inherent in new opportunities and new directions.

At the national scale, multiple parallel decisions, interventions and changes will determine the path towards the many opportunities and through the many hazards on the way to digital built Britain. In order to navigate these uncertain waters, we need a 'pole star' by which to steer our path and make myriad decisions. Defining, negotiating and procuring against a common understanding of what outcomes will create value for stakeholders, then, is the preliminary, essential and definitive step in this process. This will provide the basis for developing the data, tools and governance that define digital built Britain. Citizens, individual construction firms, city planners or service providers may not see how their plans fit into the wider landscape, but they do need access to the guidance, frameworks, processes, tools and data that will enable everyone to build a better understanding and make better decisions as they move towards their personal and shared objectives.

Technologies will come and go. At the time of writing some leaders in the construction industry have taken Building Information Modelling as the norm and are now looking at adopting digital twins. If digital twins become the norm, soon another technology will surely take its place. The common thread between each of these is the aim of making better decisions using data. That aim can be achieved using a variety of tools, but the culture, the philosophy and the decision-making processes need to be in place to exploit whatever tools are available. We need to know what outcomes we want in order to pose the right questions of the data. We need to understand how data can (and cannot) help us gain understanding. We need to have the procedural tools to transform that understanding into decisions. And we need to understand how to keep a wide range of stakeholders involved in those decisions, irrespective of the technical tools used to make them.

Whether we are swept along by currents or pilot a skilled and intentional course is up to the choices we make now about the capabilities we build, the research we undertake and the outcomes we pursue and toward which we strive. This framework is a tool to help make better decisions when faced with those choices, no matter what tools and technologies arise.

Research Landscape and Agenda

Having identified the capabilities that will need development, CDBB has explored what research might be needed to support each and what research and insights already exist that could be helpful. Summarised below and in the figure at the end of this section are research topics where there is already work and where new research would benefit the development of a digital built Britain. The research topics are coded in parentheses which relate to Figure 7 at the end of this section. The text below mirrors that of the Summary document and uses the Capability Framework as its structure.

There is an associated document (Centres of Competence) that identifies university departments and research groups that are working on, or have recently worked on, topics germane to the Capability Framework and in relevant research.

Stakeholder Value

Digital built Britain will be characterised by an increasing integration of services and built assets, as data and information are shared, new stakeholders are engaged, and sectors converge bringing new opportunities. The result will be a complex intersection of the social, political, economic, legislative and technical which will demand new tools for thinking and decision-making in pursuit of stakeholder value (VALUE). A starting point in terms of research would be to develop existing and new **explanatory frameworks** that could integrate diverse inputs from across the different disciplines (V1).

These frameworks could then enable the development of practical tools to support decision-making, prioritise future research and make better use of the insights that already exist. The tools could be underpinned by research into the best ways to engage with diverse stakeholder groups using digital technologies. The various research strands that already exist could be brought together to build and test decision-support platforms to help **translate wants and needs to specifications for procurement** within digital built Britain (V2). The multidisciplinary teams needed to build these new frameworks and tools would form a valuable resource for future work.

Although much work is being done into **business models**, especially in relation to services, there is little that focuses on models for digitally enabled services embedded in the built environment. The interplay of networks of cooperating organisations, assets and services will make identifying and rewarding value-creation ever more complex. Research is needed into the key question of **how to find ways to pay today, for value that will only be captured tomorrow** (V3).

Services

At the centre of digital built Britain will be the services (SERVICES) integrated with, and delivered through, the built environment. **Integrative frameworks** are needed to explore value and outcomes relating to these services (S1).

There is also a gap in our understanding of **the interdependencies between assets and services** and the opportunities that digitalisation will offer. Understanding the **causes and effects** relating to these interdependencies is a specific topic on which there is little research today (S2). Exploring the impact of asset performance (or degradation) on service performance (or failure) would underpin better decisions in relation to designing and managing assets and services as an integrated system.

Current research is looking at how service performance depends upon asset performance, as well as the implications of better asset management on service optimisation. However, this work is being done primarily in relation to road and rail networks. Research could usefully be extended to include different kinds of assets and services and to explore the role of digitalisation in **enhancing the design and development of services** that are closely linked with, or **dependent upon assets** (S3). Again, business model research will be important here, this time to explicitly address the ways in which investments in the design and management of buildings affects the services embedded within them, making them more or less valuable.

Built Environment

Of course, at the core of digital built Britain is its built environment (BUILT ENVIRONMENT). The **impact of the built environment on the natural environment** is increasingly recognised and research is needed into how design and planning could minimise this impact. In addition, and perhaps more significantly, research is needed into how digitalisation could contribute to managing built assets through life to minimise impact and resource use. Some work does exist, but much still needs to be done (B1).

The significance of the interaction between services and the assets on which they depend has already been highlighted. Equally, research could be undertaken into how digitalisation, data and tools could enable the **design and management of the built environment specifically to improve services** (B2).

Despite high-profile enthusiasm for digitalisation, the vast majority of the built environment consists of pre-digital assets which will not benefit from the new technologies unless the emphasis shifts. Much remains to be done if we are to take the benefits promised for ‘born-digital’ assets and provide the same benefits for other buildings and infrastructure. **Extracting data, converting it into models and using these models to manage pre-digital assets to reduce cost and environmental impact** are important topics for research (B3). We need to research specific problems in this area from which we can extract generic lessons that can be more widely applied. In particular, we need to ensure that the findings include practical approaches to address the problems that industry faces in managing new and existing assets with digital methods.

There is considerable ongoing work into new digital tools and technologies, and methods of using them in the construction sector. However, adopting such tools represents an investment risk that is often insurmountable, especially for smaller companies. Additional work is needed to **explore low-cost and low-risk entry routes** (B4) to support wider access to such tools, technologies and methods.

Data, information and models

As our management of data, information and the models (DATA) we create of built assets and services improve, so companies will need to shift their mindset and **develop new management processes that use data and models** as part and parcel of business as usual (D1). Other industries, for example aerospace, defence and offshore oil and gas, have done so for years and their insights and tools can be adapted and used in the construction sector.

Using data and models to develop better understanding and improve decision-making is predicated on the seamless and automated sharing of data, which in turn will depend on **robust structures, schemas and ontologies** (D2).

Similarly, work is needed to explore the **development of federated models linked to physical assets** (e.g. digital twins) (D3) that can be used to broaden and deepen the scope of management insight and to improve through-life management. This research can build on the considerable amount of current activity that exists in this area. The Digital Framework Task Group has set out a roadmap for much of this work while developments in models and their use offer early lessons that can be demonstrated and disseminated.

The effective use of data, information and models to make better decisions will depend upon the accurate specification of data and the integration of insight and opinion with quantitative ‘hard figures’. We will also need practical tools to gather data from diverse environments, with minimum disruption and cost, while at the same time respecting privacy and confidentiality. Research into the subtleties and practicalities of **developing and managing data sets** (D4) is currently active and is fundamental to this area.

Governance

The capabilities involved in (GOVERNANCE) provide generalisable insights and guidance for working within digital built Britain – the ‘rules of the game’. The challenge of managing regulations and standards increases as technology accelerates, digitalisation spreads and sectors, services and assets converge. Exploring the opportunities around automated compliance would encompass many key issues relating to **drafting and using regulations in a digital world** (G1).

As digital built Britain develops, sectors will increasingly converge and interact and we will need to understand how to manage standards across the boundaries. Managing **the convergence of sectoral standards** represents an important research topic (G2) that could be developed from current skills and supported by existing networks of interested parties.

As supply networks become more complex, and as digitalisation and technologies, such as distributed ledgers, throw up new opportunities, research may be needed to explore **new and digitalised contractual regimes** (G3). With the recent launch of new framework contracts, there is an established research base available which could be used.

While huge opportunities are opened up by more integrated infrastructures, increased efficiency and the growing use of digital technologies, this also carries significant risks to the smooth running of complex systems and projects. To manage these risks, we need to determine the right balance between resilience, performance, cost-effectiveness and TOTEX. Networked centres of excellence are well aware of these needs and already offer research that supports tool development and provides insights for use by policy- and decision-makers. These findings can be used to understand how to **develop and manage complex and integrated systems of infrastructure and service** in order to deliver a portfolio of objectives and manage constraints (G4). Massive potential value exists in pursuing such research further and the foundations are already well established.

Robust decision processes using data and tools in the best ways possible (G5), will be key to the success of digital built Britain, especially in a world of divergent viewpoints and uncertain data. Research into analytic tools, techniques and methods can enable such processes and there are currently networks of academics and practitioners interested and able to contribute.

Learning

The capacity to learn and adapt (LEARNING) underpins so much else in the journey to digital built Britain. Despite the optimism surrounding digitalisation, the uptake of tools and technology remains fragmented, undermining the promise of improved supply chain productivity. **Understanding the barriers to adoption** (L1), especially for smaller companies along the extended supply chains of the industry, is important to enable better productivity for all. Research to understand specific problems and identify practical ways of applying the findings is needed to accelerate the uptake of outputs resulting from a wide range of research and new technologies relevant to the industry.

Achieving digital built Britain represents a massive change programme. There is much for citizens, professionals and leaders to learn. Some of this can be achieved by developing competencies that are defined, taught and developed within the context of widely adopted **competency frameworks** (L2). Perhaps the biggest task here is to align the industry, educational and professional bodies behind such an initiative. However, research could assist by providing insights into the keys to success.

To date and in the future there will be many case studies, pilot projects and demonstrators that could be used to support learning. Many finish once their funding ceases and the stream of material dries up. Research to understand how to **maximise the sustainability and benefits of demonstrators** (L3) would make the most of existing investments.

Context

The journey towards digital built Britain will be subject to forecasted trends and jolted by events (CONTEXT) that are foreseeable in nature, if not in timing and detail. There is a large amount of research into topics such as demographics, climate change, social movements and citizen behaviours and expectations. For policymakers and planners, designers and investors, much of this research can be accessed and adapted to **detect new and changing drivers and trends** (C1), and to characterise their **probability and potential impact** (C2). Lessons from this can then be applied to the big issues that will face digital built Britain. This research can be used to create tools to **develop pre-emptive and responsive options** (C3) that will help decision-makers improve the design and management of the built environment.

A Research Landscape for digital built Britain

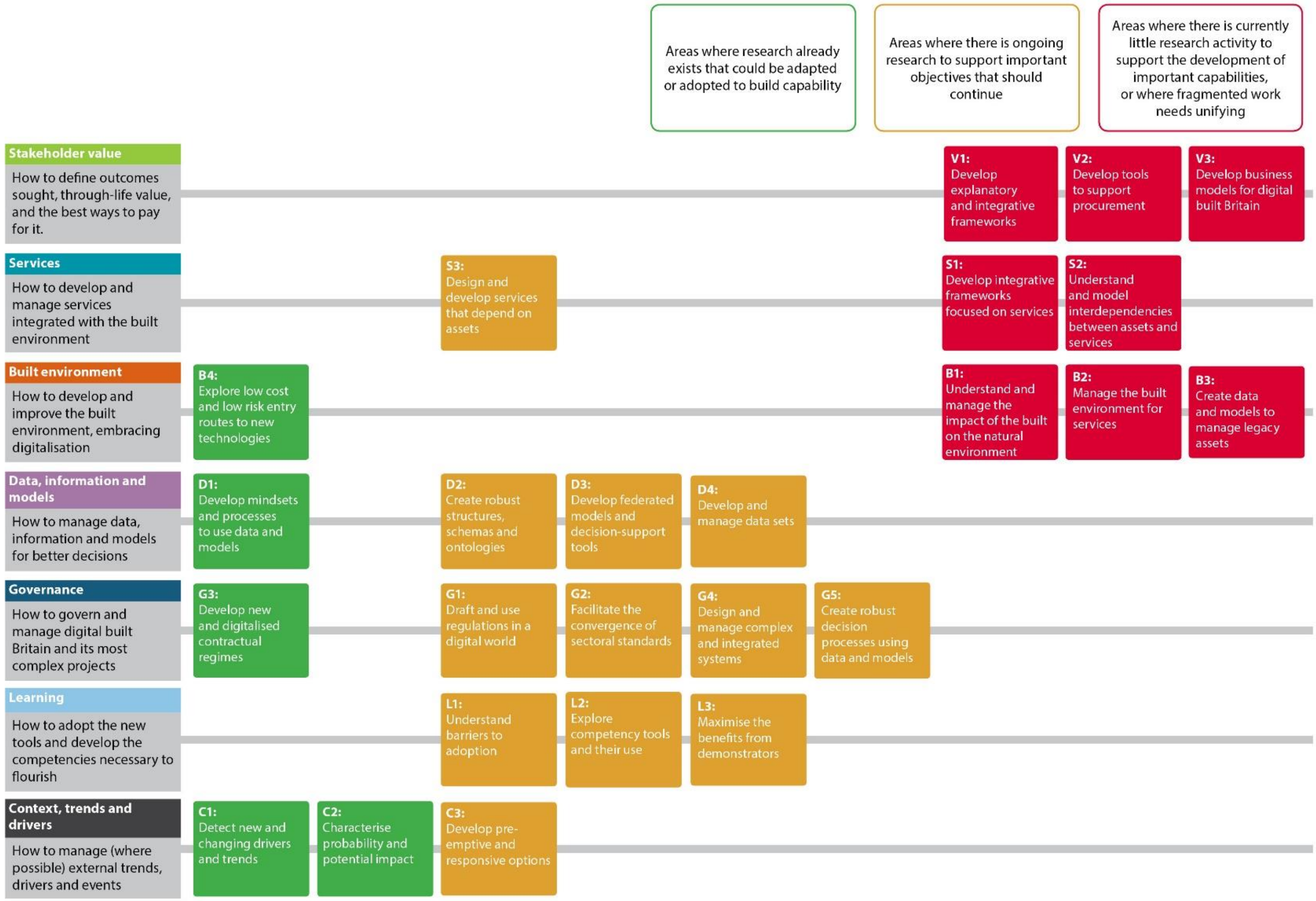

Figure 7 - Research Landscape showing research topics, clustered by capability, and characterised by available research resources and insights

Next Steps

In this document we have laid out the capabilities that the UK will need to develop over the next few decades in order to build and enjoy digital built Britain. We have also identified the research needed to achieve this and provided an overview of existing research activity in this area. From this we have mapped out a portfolio of research directions which could support the creation of the most important capabilities. We propose three main areas of focus going forward: new research, extending existing research and exploiting current insights.

Red: New research required

Firstly, we need to undertake the research needed to underpin the most important capabilities required. Perhaps the most difficult task facing the UK is to define exactly what we want to achieve in terms of a digital built Britain. Only when we have defined our objectives, and agreed the trade-offs we are prepared to make, will we be able to fulfil the vision of a digital built Britain.

Research can contribute to this by developing frameworks to support debate and stimulate new insights. By assimilating and integrating the different elements that will contribute to a digital built Britain, frameworks will also help to build a clearer picture of what is required. In addition, they will support more effective use of existing research and enable better targeting of new projects. The development of such exploratory frameworks will increase collaboration across the research base. Once developed, they can be used to underpin the creation of new tools to support negotiation, specification and procurement of the elements of digital built Britain.

Building and operationalising these frameworks will take a long time and needs to start soon. Initially, we need to take an exploratory approach, engaging widely with relevant work that already exists – and establishing who might contribute. In this way we will avoid reinventing the wheel and can bring together many isolated insights to form a much clearer and more comprehensive picture.

Research should also explore how digitalisation can shape and exploit the interactions between the services, infrastructure and assets of digital built Britain.

Very importantly, we need to look at how digitalisation can create and capture value from the built environment in order to produce a return on investments. This research into new business models is vital if we are to make digital built Britain an investable proposition and attract private sector funding to augment that of the public sector.

Further work needed in this area includes identifying how data, information and models can be used to improve the management of the vast pool of pre-digital assets – both to achieve better value and to help moderate the impact on the natural environment, through more precise measurement and management of assets. This will involve a shift in focus from digitalising the design and build phases of construction to encompass the entire through-life management of the built environment.

Amber: Extending existing research

Secondly, research can build on the considerable body of work that is already ongoing in many academic centres, to deliver both quick wins and deep insights. Various research groups are already collaborating closely with each other as well as with infrastructure owners and developers, consultants and organisations along the entire supply chain. As a result, many of the problems are already appreciated and momentum has been established. We need to invest further in this valuable work and increase efforts to disseminate the results to industry.

Research exists about topics such as standards and regulation, digital frameworks for interoperable data and models, and the planning, building and management of large, integrated infrastructures. This work could be applied in new ways to deliver quick wins and further synergies. Service development is also a focus of much existing research and this can be extended to services which are embedded in a digitalised built environment.

Much has already been invested in developing case studies and demonstrators. Research is needed to maximise the insights that can be extracted from such projects and ensure they are financially sustainable and able to continue delivering lessons of lasting value to digital built Britain.

Green: Exploiting current insights

Thirdly, there are topics that could make use of existing research capabilities and insights in this and other sectors. There is much to be learned from other sectors, such as aerospace, defence, offshore oil and gas, and manufacturing, that have already embraced digitalisation and widespread use of data, information and models in decision-making and management. Research is needed into how to adapt and apply this to the built environment and to resolve any barriers to adoption. Broader issues, concerning digital built Britain's response to trends and events, could also make use of research from other disciplines, including climate change, demographics and social trends. Such work can be used to build proactive policies to manage digital built Britain in an uncertain future.

In summary, undertaking new research into frameworks and business models, extending existing work taking place in established research collaborations, and leveraging insights from this and other sectors to accelerate digitalisation provides a robust portfolio of next steps to build the capabilities needed for digital built Britain.

Glossary

AECO	Architecture, Engineering, Construction and Operation (AECO) is shorthand for the wider collection of sectors concerned with the design, construction, operation and integration of the built environment, including buildings and infrastructure.
Asset	While in general assets may be any resource with value to an organisation, this report often uses 'asset' as shorthand for 'built asset': individual buildings and built infrastructure systems. The boundaries between individual assets and networks of assets is not explored in depth, so an 'asset' may be a building, a campus, a bridge or a whole transport network. It is a unit of built structure which an owner, commissioner, facility manager, occupant or other decision-maker needs to manage and maximise value. Where appropriate, qualifiers are added, for example 'digital asset', to identify entities that have a recognizable value.
Asset management (AM)	Asset management is a discipline and sector concerned with the realization of value from (built) assets and 'the coordinated activity of an organization to realise value from assets'. [123] (See also *Facility management*.)
Big Data	(See also *Data*.)
Building Information Modelling (BIM)	BIM is a collaborative way of working that facilitates early supply chain involvement, underpinned by the digital technologies which unlock more efficient methods of designing, creating and maintaining our assets BIM provides a digital representation of the physical and functional characteristics of an asset to support reliable decision-making and management of information during its lifecycle. At its core BIM uses 3D models and a common data environment to access and share information efficiently across the supply chain and so boost the efficiency of activities around asset delivery and operation. By helping the entire supply chain to work from a single source of information, BIM reduces the risk of error and maximises the team ability to innovate.
Capability	Different contributors to this document have used different definitions of the word 'capability'. In this report its meaning is not precise, but points to something that 'we' (see *First person plural*) are able to do in ways that are reproducible at different scales, in different contexts and/or by different parties. In particular, it builds on the value of procedural knowledge as distinct from declarative knowledge. Capabilities may well require resources, equipment and experience as well as knowledge.

[123] https://theiam.org/knowledge/introduction/what-is-asset-management/

Change agenda	This refers to the facet of the development of digital built Britain that is focused on adoption of digital data, models and tools by industry. It is seen as a separate – but connected – strand from the research agenda, especially for those elements where change does not depend upon further research.
Citizen	This report uses 'citizen' as shorthand for members of the general public who use or may wish to use the assets and services of digital built Britain. The label as used here has no implications about the residency status of those individuals. For example, tourists and international students interact with assets and services in diverse ways, while homeless individuals may miss out on value from the built environment despite being UK residents in many cases.
Data	Data here is used to mean uninterpreted bytes that – when analyzed – form the building blocks of information and knowledge that can underpin decisions. Data is not neutral or objective, but rather the product of human choices, frameworks and tools that can influence the attributes of that data and its ability to produce useful insights.
Digital built Britain (dbB)	The concept of digital built Britain is defined more fully in the summary and introduction to this document. It is a vision of the future defined by ever tighter integration of built assets and services, managed through better understanding, enabled by better data, information and models. This vision would be enabled by various advances in digital technology in the AECO sector, by new business and service models, and by investment toward outcomes that create value. (See also *AECO, Outcome*.)
Digitalisation	This is used to refer to the process of integrating digital technology, particularly technology that uses digital data to generate insights, into business models and/or processes, including (for example) supply chain management, e-governance, sharing economy, smart transport, etc. It acts beyond 'digitisation' (the conversion of current processes to digital form) by embracing new ways of working enabled by data, information and digital tools.
Digital twin	A digital twin is a virtual model of a physical asset based on real-time data, representing the current state of the physical asset and allowing for analysis, insight and interventions into the performance of that physical asset.
Facility management	Facility management (FM) is a discipline and sector concerned with the efficient operation of services and the facilities and assets that enable them. (See also *Asset management*)

First person plural / we / us / our	‘We’ and other first-person plural pronouns are used as shorthand for a vast coalition of stakeholders in digital built Britain, and it includes academic researchers, policymakers at all levels of government, business leaders, professionals and organisations in the AECO sectors. ‘We’ refers to those living, working and operating in the UK who have some role in driving the direction of digital built Britain and need to develop capabilities in order to do so. (See also *AECO, Capabilities*.)
Infrastructure	The physical structures and facilities that serve organisational, social or utility services, e.g. the built structures that make up the power grid, transport networks, ICT networks etc. Note also the distinction between ‘economic infrastructure’ and ‘social infrastructure’.
Integration / integrate	‘Integration’ refers to the condition of, or the actions to, couple together systems, assets and services, using processes, data, information and digital technology in pursuit of greater levels of effectiveness and efficiency of any and all of the component processes, assets and services. Integration may also entail organisations working together in ways that entail connections of processes and functions which may change information flows, roles and structures. ‘Integration’ is often used in the context of ‘digital built Britain’ and in this sense goes beyond the meaning of ‘systems integration’, which can be part of the development of a single asset or service.
Legacy asset	The phrase ‘legacy assets’ is used to refer to the existing stock of buildings and infrastructure, often with little or no accompanying digital data and technology.
Model	‘Model’ is used throughout the report in several specific ways. A first and most abstract use refers to ‘mental models’ which are people’s articulation of causal linkages and interactions. A second use is with respect to representational digital models, such as Building Information Models, which capture geometry, features and facilities of physical assets. These may capture and store information about the current and historical states. A third use is with respect to simulation models that compute future trajectories of the attributes of assets or services and can be used to explore ‘what if’ questions. Business models provide simulations of the value exchanges, revenues and costs for an enterprise. Each form of model can be articulated, explored and used to improve understanding and make better decisions.
Operation / operate	‘Operation’ in this report refers to the phase in the lifecycle of a building or other physical asset in which it is occupied, used and/or managed for its primary purpose. It is also the discipline of managing assets or services to specific parameters or KPIs.

Outcome ‘Outcomes’ refers to the changes arising from activities and interventions, often assessed by metrics used to determine whether value has been achieved. These outcomes may be represented by quantitative measures (e.g. KPIs, ROIs, biodiversity metrics, crime statistics, housing rates and building efficiency ratings) or qualitative attributes (e.g. wellbeing, happiness and satisfaction).

Output ‘Output’ provides a (typically) quantitative summary of an activity or of the immediate results from an intervention

Stakeholder For the purposes of this document the term ‘stakeholder’ should be considered as the widest possible collection of factions who derive value from built assets and/or services. Where ‘stakeholder’ is used to mean a more specific subset, for example investors, commissioners, planners or citizens, this will be indicated. (See also *Citizen, First person plural*.)

Value Value is derived from a set of desired outcomes (financial, social, environmental, etc.) that can be implicitly or explicitly understood. This document tends to discuss explicitly negotiated, agreed and articulated forms of value. However, as can be seen in the section discussing stakeholder value (VALUE), it is a complex topic that is best defined in relation to specific contexts and stakeholders. (See also *Outcomes, Stakeholders*.)

Index

This index provides a way into the detail of the Capability Framework using recurring themes, technologies and vocabulary that are found in the text, though are not necessarily reflected in the headings and tags of the Framework. Therefore, terms such as 'data', 'value', 'innovation' and discussions of smart cities, infrastructure and built environments, which are present throughout the document, are not indexed. The Conclusion and the Research Landscape and Agenda are also not indexed here.

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