Defining the Research Agenda and Research Landscape for Digital Built Britain

Digital tools in the creation and through-life management of built assets

Final Report

December 2018

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Foreword

The past 20 years have witnessed a transformation in digital technologies that touches every part of life in Great Britain. We now take completely for granted the ability to take digital photographs, access precise locations using satellite technologies, and access a world of information from the Internet – all from a device small enough to carry in our pocket.

Of course, these technologies affect the ways we create and manage the built environment. They will continue to evolve and continue to change how those working on buildings and infrastructure carry out their work.

This Report is the Final Report of a study carried out within the Centre for Digital Built Britain's research programme "Defining the Research Agenda and Research Landscape for Digital Built Britain". One of 9 parallel studies within the programme, this study was a response to "Tender 7: The creation and through-life management of built assets and infrastructure".

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The CAR team was supported in CDBB by Dr Charles Boulton and Julie Sigles.

Cambridge Architectural Research Ltd

Cambridge

20th December 2018

Revised for distribution 2nd May 2019

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List of acronyms used

AI	Artificial Intelligence
AR	Augmented Reality
BAS	Building Automation System;
BIM	Building Information Modelling
BMS	Building Management System
CAFM	Computer-Aided Facility Management;
CAQDAS	Computer-assisted Qualitative Analysis Software
CDE	Common Data Environment
CMMS	Computerised Maintenance Management System
EAM	Enterprise Asset Management
FM	Facilities Management
GIS	Geographical Information System
H&S	Health and Safety
IFC	Industry Foundation Class
IoT	Internet of Things
IWWS	Integrated Workspace Management System;
LCA	Life cycle Analysis
NFC	Near Field Communication
QS	Quantity Surveyor
RFID	Radio Frequency Identification
RMM	Reused Material Marketplace
VR	Virtual reality

Executive Summary

The Construction Industry employs more than 3 million people in the UK and it supports growth in all parts of the economy. However, some parts of construction are conservative and have not made the most of new opportunities offered by the digital revolution. The Government's vision of design tools combining with the internet of things and advanced data analytics could open the way for a step-change in efficiency for constructing and maintaining our buildings. It could also allow far better energy and carbon performance, reduced waste from construction, and more recycling.

This report draws together wide-ranging research of the literature (800 sources reviewed), 20 interviews with built-environment professionals, and an expert panel meeting involving 26 specialists. The report maps out current uses of digital technologies for buildings and infrastructure, it identifies the new capabilities that will be needed to fully capitalise on the potential of new digital tools – and what research is needed to develop these capabilities, as well as pinpointing the barriers to adopting new technologies and processes in construction.

The report and the research behind it have been structured around four types of digital technology:

1. **As-is reality capture** – assessing an asset at a single point in time, including point-cloud surveys (very fast laser surveys), photogrammetry (using photographs in mapping and measuring), using survey data in modelling, geographical information systems (GIS, a framework for managing and analysing data spatially).
2. **On-going reality capture** – assessing an asset over time, including sensors and monitoring (of energy use, occupancy, structural movement, health and safety, or construction progress).
3. **Information management and sharing** – storing, sharing and managing data about an asset, including Building Information Modelling (BIM, creating and managing information on a project across its lifecycle), cloud-based repositories and databases, Building Management Systems (BMS, used for managing information about a building).
4. **Data-driven decision making** – applying information to take decisions and automatic analysis and optimisation, including life-cycle analysis software (assessing the environmental impact of construction materials at each stage of extraction, use and disposal), energy modelling, benchmarking, machine learning and artificial intelligence, and cost-benefit analysis.

As-is reality capture

Our research found a strong consensus that the UK needs to improve capabilities related to specifying and processing point-cloud data. Both published literature and our expert panel meeting indicated that converting point-cloud data into a useable object model should be automated, and that this will require new skills.

There was also consensus from industry experts (both interviews and the expert panel) that adding semantic information to laser scanning models is an important opportunity. This information can be readily interpreted by machine, and it removes the problem of re-keying data for different purposes.

The difference parts of our research did not always agree about the priorities for as-is reality capture, however. While the literature review, interviews and the expert panel meeting all recognised the problem of large, unwieldy datasets. But they did not agree on the solution to this problem. The literature proposed technical solutions, like cloud servers, whereas the experts at the panel meeting said that project teams need to specify more carefully what survey data should be collected in the first place.

There was a similar divergence of opinion about surveying hidden services – a very important thread emerging from the panel meeting and interviews, but almost absent from the literature. This may reflect the different perspectives of practitioners working at the front line of construction and maintenance – facing daily challenges working with unknown and high-risk services concealed underground or in walls – as opposed to academic research that leans more towards strategic thinking and the opportunities offered by new technologies.

On-going Reality Capture

The different parts of this research were united in recommending that construction needs to be able to capture more data about occupants so that buildings meet their needs and behaviours more effectively. 'Cultural silos' between design and operation of buildings are seen as a barrier here, along with technical and technological problems with sensing and monitoring. UK universities have not carried out much work in this area, which may also have contributed to limited progress learning about occupants.

Although there was agreement that the industry needs to do more to monitor how buildings and infrastructure perform over time, they also noted problems linking sensors and monitoring equipment that is useful for design and construction to facilities management, which usually carries responsibility once an asset is handed over. Costs were also identified as a barrier to monitoring, and even though there are researchers working on on-going monitoring in the UK, take-up remains limited.

Information management and sharing

Again, a consensus emerged that better storage and exchange of data is essential. Different sources all reported that it is not possible to store digitally all the information construction professionals need – especially about end-of-life issues when components decay or need to be recycled. Our interviewees had concerns about exchanging data between BIM and other software for analysis.

Regarding sharing, we found problems transferring information from the construction stage to the operation stage, with specific weaknesses in technology used for operation and maintenance (which appear to be less mature than design and construction).

A strong theme voiced at the expert-panel meeting was the need to foster sharing of data about assets, so the industry can learn from experience and improve. This would bring major benefits, experts said, but organisations are reluctant to share data – especially about unsuccessful projects. There is also a barrier from having no centralised database to store shared project data.

Data-driven decision making

Both the interviews and literature review suggested using digital technologies to improve decision making during the design process. However, whereas the literature focused on optimising – based on multiple design criteria – interviewees focused on removing repetitious tasks and automating design.

There was also agreement that there is potential to refine and optimise buildings during operation, based on hard data. Expert panellists also saw the need to use technology to incorporate unquantifiable information (including environmental and aesthetic information) into decisions. We found lots of university research into data-driven decision making, and also practitioner organisations that are developing tools for better decision making.

Recommendations

For universities:

- Develop UK capabilities related to specifying and processing point-cloud data, turning this data into useable object models, and including semantic data in models generated using laser scanning.
- Research and develop new contractual bases to provide greater confidence in digital records and allocate risk and responsibility.
- Explore how best to monitor and record data about occupants and how they interact with the built environment in ways that feed back into the design-construct-operate-dismantle cycle and allow the industry to learn from this.

- Investigate and quantify the costs and benefits of on-going reality capture and publish case studies to help practitioners make the business case for this type of data collection.
- Support the sharing of data and information between different parts of the construction supply chain – especially from the construction stage to the operation stage.
- Provide more support to people working operating built assets, who currently appear to be less advanced in adopting new technologies for capturing, managing and transferring data and information.

For technology firms:

- Find better ways to manage large models and datasets that support the sharing of digital information and allow those using it to trust this information.
- Develop tools to discreetly, reliably and economically capture information about hidden building elements and services.
- Develop monitoring and sensing technologies that would help to overcome reliability and usability shortcomings, and also allow common platforms to be used by different parts of the supply chain (design, construction, facilities management).
- Build on existing digital hardware and software to allow storage of all the information needed to manage assets throughout their life cycle.
- Extend existing BIM software to allow accurate data exchange between software – so CAD drawings used in design can also be used for energy modelling, for example.

For practitioners:

- Support inter-disciplinary work and sharing data and information between different parts of the built environment supply chain – especially from construction through to operation, in relation to life-cycle assessment, and how construction components decay.
- Work with other practitioners to establish standards about what information needs to be transferred from construction to operation and use the standards.
- Where possible, quantify and record uncertainty digitally, so that others understand uncertainties better and appreciate when models may deviate from the 'ground truth'.
- Work with other practitioners, and industry bodies, to develop an industry capability to share insights from past projects (good and bad) and apply these in future work.
- Improve the valuation of 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.

1 Introduction and Overall Methodology

The Construction Industry is of great importance to the UK economy, employing over 3 million people and delivering well over £100bn to the UK economy. Nevertheless, it is widely acknowledged that the UK construction sector is inefficient and has low productivity. The UK Government's 2015 Strategy Document *Digital Built Britain* (HM Government, 2015) aims to change this, following other successful industries, by means of a digital revolution extending beyond Building Information Modelling. Its vision is stated thus:

> *"Over the next decade this technology (BIM) will combine with the internet of things, advanced data analytics and the digital economy to enable us to plan infrastructure (and buildings) more effectively, build it at lower cost and maintain it more efficiently. Above all it will enable citizens to make better use of the infrastructure we already have. This is Digital Built Britain."*

Moreover, given that over 80% of buildings already built are likely to still be in use by 2050, there needs to be an increased focus on understanding, modelling and managing the huge proportion of the UK's building stock that currently do not have associated digital models or information.

Digital tools will also be essential to help meet the UK's commitment to energy use and carbon emissions reduction, both through the management of energy demand, and through better understanding and management of the use, recycling and reuse of materials through the life-cycle of buildings.

This project has been designed in response to the call by the Centre for Digital Built Britain to prepare one of a number of reports which describe "the capabilities the UK will need to create, exploit and enjoy digital built Britain over the next several decades, the research agenda needed to deliver these capabilities and the landscape of research competence available today to act as a starting point". Tender 7 of the CDBB call focusses on "the creation and through-life management of built assets and infrastructure". CDBB's call asks for a report which defines:

1. What new capabilities the UK will need (and when)
2. The research, development and demonstration necessary to build, deploy and disseminate such capabilities
3. Where there is today the basis for such development and demonstration.

The current project responds to this challenge by examining present and future digital needs and opportunities for those involved at each stage of the building life-cycle: building owners, architects, structural engineers, M&E engineers, quantity surveyors, contractors, facilities managers, industry guidance bodies, technology providers and some academics.

These may include tools for: data capture and processing; surveying; sensing and monitoring; design; automation; modelling and visualisation; simulation; communication and information sharing; project management and task planning; fabrication and construction; operation; facilities management; and citizen engagement.

Since this is a topic of huge breadth, some focus is required. This study therefore gives special attention to legacy assets, and in particular to buildings rather than infrastructure. Dealing with legacy assets is a dominating factor for the UK construction industry because of space and planning constraints and because of their cultural value. Given increasing public and government concern on this matter, the study also gives a special emphasis to issues of environmental sustainability.

The three questions stated above are to be addressed but extended as follows:

- What are the current digital tools/services used and how effective are they?
- What developments are needed in existing tools, and what new tools/services will need to be/could be developed?
- What research will be needed to support such developments?
- What are the present research competences in the UK?

The research programme undertaken has four main components. First, a review of the global literature, both academic and grey literature, has been be used to structure the research domain and identify the currently understood research needs. Secondly, the literature review was accompanied by a review of the active research organisations in the UK, to assess the current UK research competencies.

In parallel with this desk research, primary data on the current use of digital tools and the associated research needs has been collected by two methods. First, by means of a set of semi-structured interviews with experienced specialists in the different disciplines involved in creating and managing the built environment; and secondly, by means of an expert panel meeting to bring specialists from different disciplines together, to identify cross- disciplinary issues, and to prioritise identified research needs

In each of the principal components of the work, the literature reviews, the interviews and the expert panel, it has been found useful to structure the research domain of digital capabilities into four broad themes which have been defined as:

- As-is reality capture
- On-going reality capture
- Information management and sharing
- Data-driven decision making

Table *1-1* explains in general terms how each of these four themes have been defined, and also lists some example technologies or processes which are included in each. These themes emerged from an early broad review of the literature. For the definition of the capabilities required in the UK, each of these research themes has been further divided into capability categories, 13 in all (Table 1-2), the scope and definitions of which emerged through combining the outcome of the literature review, the interviews and the expert panel meeting. Table 1-2 also defines categories of risks and barriers associated with the capabilities proposed, which are used in Sections 2, 3 and 4.

The primary output from this study is a set of recommendations for key capabilities identified through the literature review, the interviews and the expert panel meeting, defined in Table 1-2. For each of the capability categories, the specific capabilities required have been identified, along with associated barriers to their implementation and associated risks. The review of UK academic and non-academic organisations has been used to identify the competences available to develop the required capabilities, and gaps have been highlighted.

Table 1-1: The four research themes defining the research landscape

Theme	Description	Technologies/processes
As-is reality capture	How data about the asset at a single point in time is captured i.e. the steady state	Point cloud surveys; photogrammetry; processing of survey data to create a model; material/object recognition; condition survey; GIS
On-going reality capture	How data about the asset behaviour/ performance over time is captured	Sensors and monitoring equipment e.g. energy use inc. gas/electricity; occupancy data; structural movement; environment monitoring; construction site monitoring (H&S/progress) BMS (for information capture); RFID
Information management and sharing	How data about an asset is stored, shared, managed	BIM (elements used for information management); cloud-based repositories; databases; BMS (for information management); interoperability; modelling approaches; data format; live editing; dynamic links
Data-driven decision making	How the information gathered is put to use e.g. optimisation; evaluation; automation; decision making	LCA (life-cycle analysis) software; energy modelling; design and analysis software generally; benchmarking/validation data; automation; machine learning and AI; virtual reality;

		augmented reality; clash detection; simulation; cost-benefit analysis

Table 1-2: Capability Categories and Associated Risks and Barriers

Class	Research Theme	Code	Description
Capability category	As-is reality capture	A1	Processing of point cloud data
		A2	Surveying hidden services
	On-going reality capture	O1	Occupancy data capture
		O2	Building performance data capture
	Information management and sharing	IM1	Data storage and data exchange - interoperability
		IM2	Transfer of information from construction stage to operation stage
		IM3	Capturing and communicating uncertainty
		IM4	Sharing data across the industry
		IM5	Management of building stock data
		IM6	Keeping an up to date model and creating a single source of truth
	Data-driven decision making	D1	Building optimisation during design
		D2	Holistic building optimisation during operation
		D3	Managing waste and extracting end of life value
Risks	All	R1	Creating systems that become obsolete
		R2	Privacy
		R3	Security
Barriers	All	B1	Trust of people/commitment/responsibility for accuracy
		B2	Cost (technology, training)
		B3	Ownership of data
		B4	Lack of facilities management buy in/skills
		B5	Industry structure/status quo

The remainder of this report is structured as follows. In Section 2, the literature review is presented, its scoping and methods explained, and its results presented, separating the outcome into a global academic literature review and a review of the grey literature, focusing on the UK's output. Section 3 describes the interview programme, its aims and methods and its results. Section 4 describes the expert panel meeting, with its aims, methods and results, with a particular emphasis on the prioritization of UK capabilities which it developed. This section also gives the results of an on-line survey about technology enablers which was conducted through the panel meeting. Section 5 presents the UK competences review, linking UK academic competency to the required capabilities, and identifying active organisations outside the academic sphere. Section 6 presents recommendations for the key capabilities which need to be developed, along with the risks and barriers, and the extent to which the competence to deliver the capability exists in the UK. Section 7 summarises the conclusions of the study and considers its limitations. A full list of references is provided, and several appendices provide supplementary material as explained in the text.

2 Literature Review

2.1 Objectives

Through a review of the existing literature we are addressing the following objectives:

1. Categorise the existing research themes in this field
2. Collate the recommendations for future research identified by the academic university community as well as those captured in grey literature from non-university organisations such as institutions or government bodies.

The state-of-the-art use of digital technologies, as well as the 'readiness' of technologies has been captured through the interview and expert panel data. This approach has been adopted as it provides more up to date information and does not have a publication time lag which can be significant in relation to relatively fast-moving technology adoption.

Section 2.2 outlines our search and analysis methodology. Then, in response to Objective 2 and using the structure of the research themes and capability categories described in the introduction, Section 2.3 reviews the global academic literature to draw details of the capabilities in each category, as well as risks and barriers. The global academic literature has been used, rather than just the UK academic literature, to ensure that a lack of a research competences in the UK does not cause required capabilities to be unintentionally excluded. However, the relevance to the UK built environment has been reviewed prior to inclusion.

Finally, the required capabilities documented in the grey literature are drawn out in Section 2.4. To meet these objectives, we have reviewed in detail 50-plus documents, with approximately 35 from academic publications, and 15 from grey literature. Although significantly more have been assessed for relevance and then discarded.

2.2 Methodology

The search of literature has been undertaken as a multi-stage, iterative process and several search approaches have been employed to provide a representative and robust data set for review. To gather suitable academic publications, an on-line publication database has been interrogated using a set of relevant search terms as describe in Search 1 below. This list of publications has then been augmented using Search 2 and Search 3.

From this list, the literature reviews with the highest citation rates have then been reviewed manually to draw out the capabilities the academic community believe are required by industry. We have focused predominantly on literature reviews that summarise findings from the academic community to allow us to undertake a broad review within the limited project programme. Although some publications that are not reviews have been included where further detail was found to be required. The full set of publications identified through the searches 1-3 have been interrogated to perform a bibliometric analysis that is presented in the UK Competence Mapping in Section 5 as it provides an overview of UK research competencies rather than required capabilities.

The grey literature search used a range of approaches to gather publications, which were then reviewed manually for required capabilities, as well as current barriers and risks. This process is described under the sub-title Search 4 below.

Search 1: Search of the Elsevier Scopus citation database for academic literature

The Scopus citation database has been selected as the online search tool, both for its coverage, and ease of use. The database has 5,000 publishers, over 71M records, and 28% cover the physical sciences. Through our initial reading we have found that it is regularly used by researchers in our field of interest.

We have identified relevant terms to be used to search the 'Title', 'Abstract', and 'Key-Word' fields. These have been identified through our initial readings, previous experience, and initial conversations with academics in the domain. They align with the search terms and tool types highlighted in our bid proposal but have been refined following testing in the Scopus database.

The two overarching search terms are 'buildings' and 'digital'. All retrieved items must have both of these terms. We excluded the word 'building' due to the number of erroneous results that arose due to the use of the word by a wide range of researchers as a verb rather than a noun. Items that included 'infrastructure' were excluded due to the scope of this study.

The types of technologies that fall into the research themes are shown in Table 2-1*: Search terms by research theme used to interrogate the Scopus database* below. The search logic was formed such that the returned items must contain at least one item from any of the lists in this table. The groupings have then been used for later analysis to map the landscape (see Section 5.1).

Table 2-1: Search terms by research theme used to interrogate the Scopus database

As-is reality Capture	On-going reality capture	Information management and sharing	Data-driven decision making
"reality capture"	"sens*"	BIM	"artificial intelligence"
photogrammetry	IoT	"virtual reality"	"machine learning"
lidar	rfid	"augmented reality"	"automat*"
"point cloud"	"monitor*"	GIS	"simulat*"
"object recognition"	"internet of things"	EAM	
		CMMS	
radar		IWWS	
"laser scan"		CAFM	
"satellite imag*"		BAS	
drone			

*Notes on Table 2-1 * has been used to ensure different endings to words are not excluded; "" are used to return items containing exact phrases; CMMS, CAFM, BAS, IWWS, EAM are all types of facilities management and operation systems. CMMS – Computerised Maintenance Management System; CAFM – Computer-Aided Facility Management; BAS – Building Automation System; IWWS – Integrated Workspace Management System; EAM – Enterprise Asset Management*

In order to capture publications from all life-cycle stages of a built asset, the following search terms were applied:

"life cycle"; "through life"; "building design"; "citizen engagement"; construction; retrofit; renovation; refurbishment; mainten; operat*; "facilities management"; deconstruct*; demolish**

The search logic required that at least one of these search terms must be included. The * symbol allows for variations on the words. The word 'design' was excluded due to the number of erroneous results returned, as it can be applied to any research where a tool or approach is designed from any discipline.

The results of this search were then refined to only include journal and conference papers, from 2014-2018 inclusive, and written in English. In addition, they were required to be from the following Scopus defined subject areas: *Engineering; Computer Science; Energy; Social*

Sciences; Environmental Science; Mathematics; Materials Science; Business Management and Accounting; Decision Sciences; multidisciplinary.

The search has not placed geographical restrictions on the retrieved data. This is done in the subsequent segmentation, in the bibliometric analysis in Section 5.1

The data exported from Scopus includes citation count, and this has been used to create a metric of 'average citation count per year', through which the most cited articles can be identified for further review.

The manual review is a two-stage process. Initially, the abstract is read for relevance and insufficiently relevant papers are discarded, then the full article is reviewed. Limitations to this search arise from two key sources: the search terms used to interrogate the Scopus database and the content of the Scopus database itself. The former we addressed through two approaches:

- **Verify that the search terms are not too broad:** Once the list of publications was extracted from the database, we reviewed a sub-set manually to check that the number of erroneous results was very low.
- **Verify that the search terms are not too narrow:** This was addressed iteratively by considering throughout the project whether any additional terms should be added to the search lists.

Any limitations, arising from the extent of the data within the Scopus database itself, we have addressed by reviewing the results of the initial analysis against recommendations made through our conversations with active researchers in this field.

Search 2: Review of CDBB community

In order to ensure that work produced through the CDBB, that may not be captured by Search 1, was appropriately considered, we reviewed the CDBB website for publications. Care was taken to ensure that any biases of focus, due to Cambridge University's prior research competencies, were avoided.

Search 3: Capture Wildcards

Through conversations with experts in the field, additional publications were recommended for inclusion in our review.

Search 4: Grey Literature

Key organisations were identified through the following means:

1. determining the key disciplines in the life-cycle and looking to their professional bodies
2. speaking with members of the industry
3. identifying key players through the Digital Construction Week conference
4. extracting non-academic partners from academic literature

Within these organisations, the knowledge databases were then searched through their websites using the terms “digital” and “buildings”. In almost all cases this was sufficient to elicit a comprehensive and manageable set of results. In databases where large numbers of erroneous results were still found, the further search term “sustainability” was added.

The results from these searches were then reviewed in two stages; firstly, by title and summary, after which irrelevant results were discarded, and then by full reading.

2.3 Global Academic Literature Review

This section provides an overview of the required capabilities and recommendations for future research as identified by the global academic community. Due to the size of the body of literature in this field, this review has focused on collating the recommendations from published literature reviews, rather than primary research. Prior to inclusion, the requirements are reviewed for relevance to the UK built environment.

Our analysis of this body of literature revealed areas where researchers have indicated that there are under-researched topics, or opportunities that have not been exploited. Where these align with the required capability as identified through the interviews and the expert panel, the literature has been reviewed in depth to detail the requirement as see by the academic community. Therefore, this literature is uses Capability Categories as structure.

Although a large selection of published work has been reviewed and summarised here, there are several key and recent literature reviews that are particularly informative contributions given the scope of this report, and worth noting. The relevant finding included in these works are discussed under the Capability Category in the main body of this section.

The research area of the digitisation of facilities management is explored in detail by Wong *et al.* (2018). Through a review of 120 papers, they explore the state of the art in Building Information Modelling; reality capture; the Internet of Things and geographic information systems (GIS). Key overarching conclusions from their work include improved interoperability; processes surrounding point-cloud data and effective integration of BIM with GIS data. Wijekoon *et al.* (2018) also interrogated this research area, confirming the value of the information exchange from the construction phase to the facilities management stage and concluding that there are currently barriers to realising the full potential including: limited understanding of what information should be exchanged, as well as lack of awareness of the value it can generate.

Several researchers have looked specifically at the impact of the current status of BIM on the environmental sustainability of buildings. The literature investigating the integration of Building Information Modelling with Life-Cycle Assessments (LCAs) has been reviewed in detail by Soust-Verdaguer *et al.* (2017). They find that much of the existing literature (including the case studies) focuses on new buildings, rather than existing buildings, and has predominantly looked at the energy life-cycle. Soust-Verdaguer *et al.* make a range of recommendations for future research that are discussed in more detail later in this section. Wong and Zhou's (2015) review of 84 'Green-BIM' papers found that there is relatively little focus on maintenance, retrofitting and demolition, with significantly more focus for the design and construction phases. Wong and Zhou also put forward a set of recommendations for future research that are included in the main body of this section.

Finally, there is a cluster of work that explored the exiting literature in digital technologies for existing buildings. Ilter and Ergen (2015) review the literature for BIM for building refurbishment and found unresolved research themes around building surveying, energy management, management of maintenance information, and data exchange and interoperability. Khaddaj and Srour (2016, p.g. 1532) also review the literature of BIM for retrofit, but through the lens of sustainability, and conclude that BIM still has "technical, informational, and organisational" barriers. Volk *et al.* (2014) reviewed 180 papers looking at BIM for existing buildings and concluded that there is relatively low adoption of BIM in this area. Their recommendations are discussed in further detail in the main body of this section.

The rest of this section is structured using the Research Themes identified in the bibliometric literature review: As-is reality capture; On-going reality capture; Information management and sharing; and Data-driven decision making. Under each heading the key required capabilities identified through the literature review are drawn out and discussed. At the end of the section, commonly reported risks and barriers are discussed.

As-is reality capture

Point-cloud surveying (A1)

Within the Research Theme of As-is Reality Capture, the gathering and post-processing of point cloud 3D laser scanning data is regularly identified an active area of research, but nonetheless inadequate for current needs (Wong, Ge and He, 2018; Ilter and Ergen, 2015; Bruno, De Fino and Fatiguso, 2018; Volk, Stengel and Schultmann, 2014). The academic community argues that once it is possible to generate a base model of the asset efficiently, the broad benefits of BIM can be unlocked for existing buildings. Although it is a widely discussed topic, it is possible to draw out a few key required capabilities:

- Due to the time-consuming nature of processing the point-cloud data into object oriented models there is a need to automate this process (Ilter and Ergen, 2015; Bruno, De Fino and Fatiguso, 2018; Wong, Ge and He, 2018).

- Facilitating the generation of semantically rich models by adding attributes to the object, is a key area of focus. Ilter and Ergen (2015) highlighted the need for the research community develop methods for collecting semantic data (such as material or structure type) during the laser scanning. Following this, in 2018, Wong *et al.* (2018) called for the development of algorithms for reliable object recognition. Sanhudo *et al.* (2018)called for the ability to capture energy related data such as thermal properties as part of the surveying and model generation process to support the use of BIM for energy retrofitting.

- Point cloud data is generated in large data sets and there is a need to develop methods of managing the scale of this data. These may include the use of cloud servers to augment processing power (Volk, Stengel and Schultmann, 2014), or methods to retain required accuracy with file downsizing (Wong, Ge and He, 2018).

Surveying hidden services (A2)

This capability category has been included in the report due to the evidence for its need found through the interviews and expert panel. However, there is very little literature from the global academic community in the last five years that is relevant to this topic. Liu and Seipel (2018) discuss using augmented reality to assist facilities management operatives in finding known services, however, this does not cover detection of unknown services. By deepening the literature search, it has been possible to find research that looks specifically the most effective frequencies for ground penetrating radar (GPR) to find below ground services (Bianchini Ciampoli *et al.*, 2016), although this work does not include an investigation of integrating this data with an broader digital model. Thus, it has not been possible to draw out the capabilities in this filed that the academic community have put forward.

On-going reality capture

Occupancy data capture (O1)

In their review of the impact on occupant behavior on building energy use, D'Oca *et al* (2018, p.g. 732) note that household energy use can vary by a factor of 3-10 due to "human factors", although it should be noted that this range is aggregated from studies in a range of climates. As a result, they emphasise that there is a need to understand the relevant human behavior to reduce operating costs and improve comfort and suggest that Internet of Things technologies could be used to gather relevant data (D'Oca, Hong and Langevin, 2018). De Wilde (2014) also highlights this need, indicating that an understanding of human behavior and experience is necessary to close the current energy performance gap (i.e. the difference between that anticipated during design, and that found during operation).

In their study for the CDBB, Navarro *et al.* (2018) note that there is particular need to understand the occupant's experience of transient effects, such as changes in temperature, air quality and vibration, and their impact on occupant satisfaction and productivity. They highlight the cost, reliability and accuracy of suitable sensors as barriers to capturing this data. Naghiyev *et al.* (2014) undertook a review of technologies used to measure occupancy in domestic buildings and concluded that current technologies do not produce reliable data.

Building performance data capture (O2)

The academic literature focuses on two areas of building systems performance data capture. De Wilde (2014) suggests that to close the performance gap in building energy use, it is necessary to increase the amount of data captured about the actual energy usage. However, although there are many technologies available on the market for monitoring the electricity use on a circuit, technologies to monitor energy use in the form of gas are less well developed and important to capture domestic heating energy use which is a substantial part of domestic building energy consumption (Palmer *et al.*, 2015).

The academic community are also investigating methods to capture data that might indicate faults with existing building systems. For example, Bruton *et al.* (2015) reviewed fault detection systems for air handling units (AHUs) and concluded that for the existing technology and integrated fault detection systems to be adopted, the economic benefits must be researched and documented to allow potential users to construct a business case.

Information management and sharing

Keeping an updated model and creating a single source of truth (IM6)

The existing literature calls for the capability to maintain the model by updating it as the asset changes, as well as the capability to consolidate the information about an asset. These required capabilities parallel the concept of Digital Twins.

From their review of the existing literature, Wong *et al.* (2018)draw out the need to facilitate updating the information contained in the model with a particular focus on maintaining the as-built information during the Facilities Management life-cycle stage. They draw out the need to automate these processes. In their review of BIM for existing buildings, Volk *et al.* (2014)also concluded that the maintenance and updating of information within the BIM is a key challenge.

Chen *et al.*'s (2015)literature review, further reinforces this point, highlighting the need to maintain consistency between reality and the BIM in real-time.

Data storage and data exchange – Interoperability (IM1)

The ability to store the required data, and importantly exchange it with other disciplines and softwares is a strong theme that runs through much of the literature. It is clear that the current data schemas are insufficient for current needs.

- In the context of Facilities Management (FM) systems, Wong *et al.* (2018) note that there are no systems that can manage the range of information relating to all the different functions of an FM department. They recommend that the future research agenda should address this "fragmented" structure of FM software, and recommend development of effective open data standards. Ilter and Ergen (2015) also note the large number of different softwares used in FM and suggest research is required into both the specification of information exchange (i.e. what need to be exchanged) as well as data exchange standards such as IFCs (i.e. how it can be exchanged).

- Following on from the heading above (*Keeping an updated model and creating a single source of truth)*, Chen *et al* (2015)suggests that improved interoperability between BIM or FM systems and data acquisition technologies may facilitate the maintenance of an up to date model, and that there is a lack of studies in this area to confirm specific needs.

- Several reviews highlight areas where there are no schemas to store the data:

    - Ahmadian *et al.* (2017) and Soust-Verdaguer *et al.* (2017) note that current BIM attributes are insufficient for the deconstruction life-cycle stage;. This may be one of the issues that contributes to the low activity in the area of digital technologies for deconstruction. This feature of the research landscape has been identified in the this bibliometric analysis in this report, and noted by the research community (Wong and Zhou, 2015).
    - A second example, identified by Bruno et al. (2018) is the current lack of ability to store information relating to decay, and the limited IFC classes that can store structural diagnostic data and data from structural sensors.

- o Finally, Khaddaj and Srour's (2016) review of using BIM to retrofit existing buildings, highlighted the need for the development of new Model View Definitions, and extensions to the current COBie schema, which currently are tailored to new buildings rather than the information transfers related to retrofitting existing buildings.

- Energy analyses, and Life-Cycle Analyses (LCAs) are active areas in the research community. Issues in this area fall into two topics: interoperability between BIM software and different analysis tools (Khaddaj and Srour, 2016; Soust-Verdaguer, Llatas and García-Martínez, 2017; Sanhudo *et al.*, 2018); and the ability of BIM software to store the necessary data (Soust-Verdaguer, Llatas and García-Martínez, 2017), creating a single source of required information (Wong and Zhou, 2015). Soust-Verdaguer *et al.* (2017)list several areas where current BIM software is limited in capturing information that is valuable to a truly 'through-life' LCA, these include: recycling, reuse and repair.

Transfer of information from construction to operation life-cycle stages (IM2)

The handover of information at the end of the construction phase to the facilities management team is a clear pinch-point in the flow of information through the life of the asset. The academic community has identified required capabilities as well as the current barriers to the adoption of existing technologies.

- Many of the reviews of existing literature, conclude that there is lack of understanding of what information should be transferred from the construction team to the FM team at completion and handover (Wijekoon, Manewa and Ross, 2018; Wong and Zhou, 2015; Wong, Ge and He, 2018; Volk, Stengel and Schultmann, 2014). Both Wong *et al.* (2018)and Wijekoon et al. (2018) suggest that that a barrier to developing this understanding on a specific project may be the late appointment of the FM team in the project life-cycle. The result of this is that when the information transfer requirements are confirmed and contractually agreed by the design and construction teams, the users of this information, the FM team, are not available to specify what they will need. It is not clear from the literature which of the following approaches is most needed: research to understand the information transfer requirements on any project; or a change to asset procurement that makes the FM team available at the point in the project when the information transfer requirements are confirmed, although both are discussed.

- Extending the discussion under the above heading (*Data storage and data exchange – Interoperability),* Wong et al. (2018) and Ilter and Ergen (2015), highlight the need for improved data exchange between BIM and FM systems, suggesting that data exchange standards require development. Ilter and Ergen (2015) suggest extension of the open source IFC schema.

- The capability to generate an accurate as-built model at the end of the construction phase, or to efficiently maintain the accuracy of the model during construction, reduces the costs of model generation during the operation phases. Wong *et al.* (2018)note the potential value of maintaining an up-to date model during construction that would be ready for transfer to the FM systems and conclude that current image based surveying and automated model updates require more research work. Gimenez *et al.* (2015)review the existing literature that covers creating an as-built model by reconstructing the 3D model from 2D information and conclude that although advances have been made in several steps of the process, a full 'generation chain' is not yet available.

Capturing and communicating uncertainty (IM3)

Several studies highlight capturing and communicating uncertainty as a required capability and note that existing digital technologies are insufficient in this area.

- In the context of BIM for existing buildings, a key conclusion from Volk *et al's* (2014) review is the requirement to be able to model uncertainty of the data. They refer to the uncertainty of the modelled objects themselves as well the relationships between them. They include a list of the IFC data schema extensions required to capture uncertainty including: measurement errors; concealed objects; uneven floors/walls (Volk, Stengel and Schultmann, 2014, page 116). Khaddaj and Srour (2016) also highlight the need to capture uncertainty during refurbishment activities and refer to uncertainties surrounding cost, time and energy consumption.

- Molina-Solana *et al.* (2017)reviewed the existing literature relating to data science for building energy management. They discuss in depth the issues around managing uncertainty and imprecision that they group into three categories "(i) physical uncertainties inherent in physical properties, which appear in quantified measurements; (ii) design uncertainties, such as changes in the room geometry or the window size; (iii) scenario uncertainties that are linked to building usage" (Molina-Solana *et al.*, 2017, page 607), and conclude that this is a remaining challenge.

Sharing Data across the industry (IM4)

Several studies have noted the potential value of sharing asset data across the industry to support decision making. To improve the industry's understanding of the energy performance of buildings, De Wilde (2014) suggested that sharing performance data would allow groups of similarly performing assets to be identified. On similar theme, Ilter and Ergen (2015) suggested that the availability of data from retrofit projects would assist in future retrofitting decisions.

Linden *et al.*'s (2018) interview-based horizon study for the CDBB found that some data is currently being shared, but the "fragmented" nature of this sharing limits its usability. They highlight that there is risk that lack of standardisation and coordination may become barrier to the full potential of Big Data to support improvement in the built environment.

Management of Building Stock Data (IM5)

Mastrucci *et al.* (2017) reviewed the use of LCAs for building stocks and suggested that there is potential to use this approach to identify urban zones where buildings energy consumption could be reduced through refurbishments. This can be used to support government policy. To facilitate this, Mastrucci et al. suggest that there is a need to be able to aggregate building stock data and incorporate spatial constraints. They recommend that this be supported by improving the integration of building stock data, 3D semantic models and GIS data. On a similar theme, Wong *et al.* (2018). recommended improved integration of BIM and GIS data and suggested prototype systems should be developed.

Data-driven decision making

Building optimisation during design (D1)

The existing literature explores the use of digital technologies to support decision making during the design process. It discusses analysis and evaluation tools, as well as the availability of data to form the basis of the decisions.

- Eleftheriadis *et al.* (2017) in their review of LCA approaches combined with BIM capabilities for the development of energy efficient structural systems, concluded that there is a need for decision-making tools that make recommendations and allow teams to understand the effectiveness of decisions in real time.

- In their investigation of the energy performance gap, De Wilde (2014) calls for greater availability of validation and benchmarking data, as well as improved forecasting. De Wilde (2014) notes that benchmarking data may include acceptable alignment between prediction and reality, or for comparison of performance between building stocks. Whereas Firth *et al,* (2015) in their study of smart home technology, note that benchmarking can be used to compare a single home's energy consumption against other homes to support decision making by the user.

- Mat Daut et al. (2017) reviewed the existing literature in electrical energy forecasting and concluded that conventional methods can be combined with Artificial Intelligence (AI) to improve the precision of the results. Miller *et al.* (2018). reviewed machine learning technique to interrogate building performance data for activities such as retrofit analysis and concluded that further collaboration was required in the research community to exploit the potential of this technology

- D'Oca *et al.*'s (2018). review of the influence of occupant behavior on building energy use concluded that there is a need to fully integrate occupant behavior into the decision-making process during the design phase, as well as operation, by making use of data and modelling

Holistic building optimisation during operation (D2)

During the operation life-cycle stage, the existing literature focuses on energy demand management, and controlling the building's internal environment. The topic overlaps with automation of the related building control systems.

- Beudin and Zareipour (2015)reviewed home energy management systems and concluded that to support automated decision making, there are still capabilities required including: improved multi-objective optimisation algorithms; access to sufficient processing power; and effectively modelling consumer well-being. Molina-Solana *et al.* (2017) highlight that the cost saving opportunities presented by effective energy demand management calls for the research community to develop methods of manage the large data sets generated in real-time.

- Konstantoglou and Tsangrassoulis (2016)reviewed the literature for automated daylight and shading systems and concluded that for greatest energy reduction, the systems should be integrated with other building control systems such as lighting.

- Haq *et al* (2014).concluded that an increased understanding of occupant behaviour is necessary for the development of automated lighting control technologies.

Managing waste and extracting end of life value (D3)

Relatively little of the global literature specifically considers managing waste and extracting end of life value and so it has not been drawn out as a key theme in literature. However, it was drawn out of the interviews and expert panel, and so has been included here briefly. Liu *et al.* (2015) note that the existing academic literature agrees that BIM has the potential to be used for Construction Waste Management (CWM) during the design stages, however, they note that there is a lack of tools that can support decision making.

Risks

Several pieces of academic literature make reference to the risks around data privacy and highlight that these will need to be managed and mitigated as increasing amounts of data, including potentially personal data from occupants, is captured (Linden, Almond and Patterson, 2018; Navarro *et al.*, 2018; Molina-Solana *et al.*, 2017; Jalia, Bakker and Ramage, 2018).

Linden *et al.*'s (2018) interviews with experts in the field noted that these risks of privacy are on an individual level but also relate to commercially sensitive data. Navarro *et al*, (2018) also raise this risk in their study that focuses on capturing occupant comfort and productivity data. Molina-Solana *et al.* (2017) highlight both privacy and security risks in the context of big data. Whereas Jalia *et al.* (2018) in their case study of The Edge office building in Amsterdam, note that the public's perceptions around data privacy is potentially a barrier to gaining acceptance from building occupants to capture useful data about their behavior. This suggests that, failure to manage this risk may create a barrier to the adoption of related technologies.

To a more limited extent, the literature highlights that there is risk arising from the lack of understanding of how digital visualisations influence the behavior of those interacting with them (Linden, Almond and Patterson, 2018). On a similar themes, Jin *et al.* (2018). note that the visualisations that they developed for city design were effective for use by specialists, but the efficacy when employed for communication with the public is currently unknown and requires research

Barriers

From the existing literature it is clear that there is a lack of effective deployment of digital technologies for facilities management, and several researchers look at the barriers to this. A key conclusion is that there is a lack of awareness of the value of digitisation for facilitates information management (Wijekoon, Manewa and Ross, 2018; Wong, Ge and He, 2018), and there are recommendations for further case studies as well as the develop of enablers for cost-benefit analysis. Ilter and Ergen (2015) also note that there are organisational barriers relating to culture. Volk *et al.* (2014) and Wong *et al.* (2018) conclude that there is a requirement for training and education of facilities managers in the maintenance and use of BIM-like FM systems

The key barriers to sharing data, both to allow for interrogation to evaluate designs, but also to avoid rework on a specific project, relate to copyright and ownership. *Wong et al's* (2018) review of digitisation of facilities management suggested that issues with ownership of data might be resolved with licensing agreements, but it remains a current barrier. Jalia *et al* (2018) noted that complications around who owns the data (the tenant, the building owner, or the original developer) could present a barrier to its use. Linden et al. also highlight current data ownership as a barrier to the availability of information with both governments and private companies owning large data sets but not making them available. They recommend government policy intervention to address this issue (Linden, Almond and Patterson, 2018).

Finally, Volk *et al* (2014) conclude that there is a lack of cost benefit analyses that focus on the use of BIM for existing buildings. Lu *et al* (2014) note the lack of cost-benefit analysis generally and note that further work in this area is restricted by the lack of relevant data.

2.4 UK Grey Literature Review

Based on the categorisation system which arose through the data gathering, several strong topics arose in the search of the non-academic literature.

It is widely accepted in industry publications that digitisation is beneficial not only to the industry, as a whole, but to individual businesses. This has been shown through the experiences of survey respondents (Microsoft and RIBA, 2018; NBS, 2018). In fact, it is often expressed as a necessity for survival in the coming years. The key benefit is seen as improved efficiency at all stages of a project, both through technical work and "back-office" procedures, such as communication and collaboration.

Cost Barrier (B2)

While looking at the potential of digitisation in the industry, several institutions have looked at what is holding the industry back, as it is widely recognised that the construction industry is the least digitised industry in Europe (Barbosa *et al.*, 2017).

While the available benefits of digitisation are not disputed in any found publications, there is a widespread recognition of the high upfront cost required to access such efficiency increases (Brilakis, 2016; Microsoft and RIBA, 2018; NBS, 2018). This cost is identified as not only being the systems themselves but also in the training and time spent on transition (Kemp *et al.*, 2017; Microsoft and RIBA, 2018). It is also regularly stated that a lack of client buy-in is holding companies back from investing in the technologies and training, particularly in the operational life-stage (Thomas, 2017; Microsoft and RIBA, 2018; Pinder and Ellison, 2018). In addition, for SMEs, the lack of client buy-in also affects the uptake of technologies for the construction and design and planning phases.

Usage Guidance

While guidance documents on why and how to implement existing digital technologies are not hard to come by in existing knowledge databases (Hobell, 2015; Brilakis, 2016; Smith, 2016), the depth of knowledge communicated is limited, as is the potential for industry disruption. Such guidance documents are available for all key disciplines, with the largest numbers covering the design and planning, and construction life-stages.

The limited knowledge depth in these documents is usually due to the large number of variations and systems available within a single "digital technology". For example, GIS can refer to several different products and their outputs (maps) for which there are many different applications (Kirkup, 2015). As such, the guidance generally covers over-arching uses of such technology, rather than specific technical guidance on how to successfully implement it.

In addition, this guidance seems to come about once industry has accepted such a technology, to improve widespread uptake, rather than to introduce the technology to industry in the first place. These documents often appear in the form of a pros/cons list with recognition of potential barriers to implementation, which may influence a company's decision to take up the technology (Kirkup, 2015; Hobell, 2015).

Due to the shallow nature of this guidance, there is little open information on how best to choose individual systems for a company or project and opens the industry up to the risk of ineffective uptake and use of technologies.

Data exchange and storage – Interoperability (IM1)

The industry publications are aware that change in the built environment sector cannot wholly be addressed internally, and as such external input is also required in order to successfully digitise the sector (Adonis, 2017; Kemp *et al.*, 2017; RIBA and ARUP, 2017).

One issue which comes up time and again is data interoperability. There may be many systems out there, but they cannot speak with one another, as they are developed as closed systems (Whyte, 2015; Brilakis, 2016; Smith, 2016; NBS, 2018). The idea of a set of standards for data transfer and sharing is often floated as a way to increase the uptake and performance of digital technologies at an industry scale (Beart, 2016; Adonis, 2017). Although there are open source interoperability standards available to, and used by the industry, such as IFCs, the literature suggests that the issue is not fully solved by these standards as they currently exist.

Data sharing and security (IM4 and R3)

With ever increasing data being created and gathered on public projects, there is a call for this data to be used to inform future projects (Adonis, 2017; RIBA and ARUP, 2017). The ability for people to share and access such data securely and reliably, would, from the point of view of industry, enable the industry, as a whole, to operate more efficiently.

However, the nature of the industry structure places a barrier to this open sharing and the security of any shared data, particularly of large physical assets, is a major concern (HM Government, 2015; Adonis, 2017; Kemp *et al.*, 2017; Microsoft and RIBA, 2018; NBS, 2018).

3 Interviews

3.1 Objectives

Semi-structured interviews were used to gain an in-depth understanding and explore the current use of technology in the built environment sector, with a particular focus on digital technologies used in the management of legacy built assets. Interviews help to cross the gap between industry and academia and explore viewpoints which are unclear in both the academic and grey literature. As no hypothesis was set at the start of this study, the purpose of the interviews was an exploratory investigation using an inductive analysis which allowed patterns to be built up from the data and generate new theories (Creswell and Creswell, 2018; Schwandt and Gates, 2018). Quantitative methods were not used as these are better suited to testing theories (Gillham, 2000).

3.2 Methodology

3.2.1 Interviewee Selection

When conducting interviews, it is important to define who is participating and why they were chosen. For this study, purposive sampling methods were used to select the participants, meaning that they were chosen using known-characteristics including they had experience working with digital tools within the built environment, specifically on legacy assets and could be described as sitting within one of the disciplines defined through the literature review (Section 2). Two types of purposive sampling were used: ‘convenience sampling’ and ‘opportunistic and snowball sampling’ (Kemper et al., 2003). Convenience sampling was used as selected participants were former contacts of the researchers within the CAR research team and were people that were ‘conveniently available’ as well as willing to take part in the investigation (Collins, 2010). Opportunistic and snowball sampling was used as the other participants were people the research team had met at events such as the Digital Construction Week (attended 17/10/2018) and/or those suggested by others identified in the convenience sample. In total 21 interviews (22 interviewees) were conducted between 12/11/2018 and 03/12/2018, covering a range of disciplines (see

Table 3-1).

Table 3-1: Number of interviewees in each stakeholder category

Discipline	**Number of interviewees**
Design Engineer (Global Org)	1
Estate Manager	3
Industry Guidance	1 Facilities Management
Architect	1 Lecturer, 1 Researcher
M&E Engineer	3
Main Contractor	2 Construction, 1 Demolition
Property Manager (Futureproofing)	1
Quantity Surveyor	1
Researcher	1 Building Performance, 2 Circular Economy
Structural Engineer (SME)	1
Technology Provider	2 BMS, 1 Digital Surveying, 1 Preventative Maintenance
Total	22

Participants were recruited by sending an invitation via email briefly explaining the project. If interested, the participant was then provided with an 'Interview Participant Pack' (provided in Appendix A). This described the aims of the project, funding, benefits to the participant and what would happen with the collected data; a consent form (which included a request to record the conversation) and a breakdown of questions that might be asked, alongside a glossary of key terms. Only core/general questions were included in the pack, rather than potential follow-up and focused questions to avoid steering the conversation in a particular direction. Once the participant consented to the interview, a time and location was organised.

3.2.2 Interview Preparation and Format

The literature review was used to identify what aspects, related to digital tools and the lifespan of existing buildings, needed exploration or validation using expert viewpoints. The questions were designed to lead to the different research outputs outlined in Section 1, including capabilities; risks; barriers; attitudes; effective enablers, as well as contributing to the technology map (Section 0) and defining the population using digital tools. A breakdown of the core questions is provided in Table 3-2, alongside a description of which research output is the most applicable. These questions were designed using guidance from well-known texts in conducting qualitative research including: Bryman (2008); Creswell and Creswell (2018); Robson (2011); Silverman (2013). Open questions were used which invite descriptive answers. Once defined, the questions were put together in an interview guide. As the interviews were semi-structured, this was a guide rather than a fixed set of questions and it allowed the interviewer to follow-up on particular topics during conversation if they thought further elaboration was required, these follow-up questions ensured that the relevant research outputs were recorded (Bryman, 2008). Due to logistics and time-constraints all interviews took place via the telephone. The length of interviews ranged from 10 minutes - 50 minutes, with the majority taking approximately 30 minutes.

Table 3-2: Breakdown of questions and relevant research output

Core Questions	Relevant research output/purpose
Could you please tell me how you are involved in the management of existing buildings?	Define population working with digital tools.
What digital technologies do you currently use on a regular basis in this role, with regard to existing buildings? Please could you also explain their functions, at which point in the process it is used and their efficacy in more detail?	Develop 'Technology Map' showing what technologies are currently used (Section 0).
What are the main benefits of using these digital technologies in existing buildings? What are the main drawbacks of using these digital technologies with existing buildings and how could they be overcome?	Defines the efficacy of technologies included in the 'Technology Map'. Drawbacks indicate current capabilities. Benefits/drawbacks indicate differing attitudes.
What seem to be the main barriers to uptake of digital technologies for the management of buildings through their lifespan?	Indicates the main barriers to technology update

With new technologies becoming available, are there any which you are planning to implement on projects in the near future (and why)?	Indicates capabilities, specifically future opportunities.
Are there other areas of your work with existing buildings where new digital technologies could be beneficial?	Indicates capabilities, specifically the need to using new technologies.
What do you consider to be the major risks of implementing more digital technologies in the industry?	Identifies perceived risks.

3.2.3 Data Analysis

All the conversations were recorded using a voice recording app called 'Cube ACR' and notes were taken by the researcher. The notes were then word-processed and collated into an interview note template (see Appendix B) which was designed to reflect the desired outputs of the research questions and helped to structure the primary data ready for analysis. If required, the voice recordings were then used to validate the notes and aid the interviewer to ensure all the key points were covered.

Once the interview notes had been assembled, a Computer Assisted Qualitative Analysis Software (CAQDAS) was used to 'code' the interviews, meaning the use of a word or phrase to describe what the interview participant was talking about. Interview data can be coded in a variety of ways, including line by line or different topics of conversation. For this study, the interview notes were coded sequentially. Initially 'chunks' of text related to the life-cycle stages was identified; then with this, the coding was narrowed down to identify specific technologies and the desired research outputs: risks, barriers, effective enablers and attitudes. This meant that 'chunks' of text have multiple codes attached (see Figure 3-1).

An initial list of codes was formulated during the literature review, these were then built upon during the analysis as new topics were identified during the conversations. An initial set of coding all interviews was conducted, followed by a discussion with the research team to identify where there was potential overlap between the codes which had emerged. The codes were refined and a second iteration of coding was completed. The CAQDAS was then used to count the number of interviews where a particular code was discussed. This allowed the researchers to identify topics which were regularly discussed which was then used as an indicator of their importance (Creswell and Creswell, 2018). The number of people discussing a code has been defined rather than the number of times a code was mentioned within the interviews as the data could easily be skewed if an interviewee regularly referred back to the same topic during conversation. The software was also used to view all the notes/information about a code on one page, which was useful in compiling recommendations and identifying what the different participants said about the same topic.

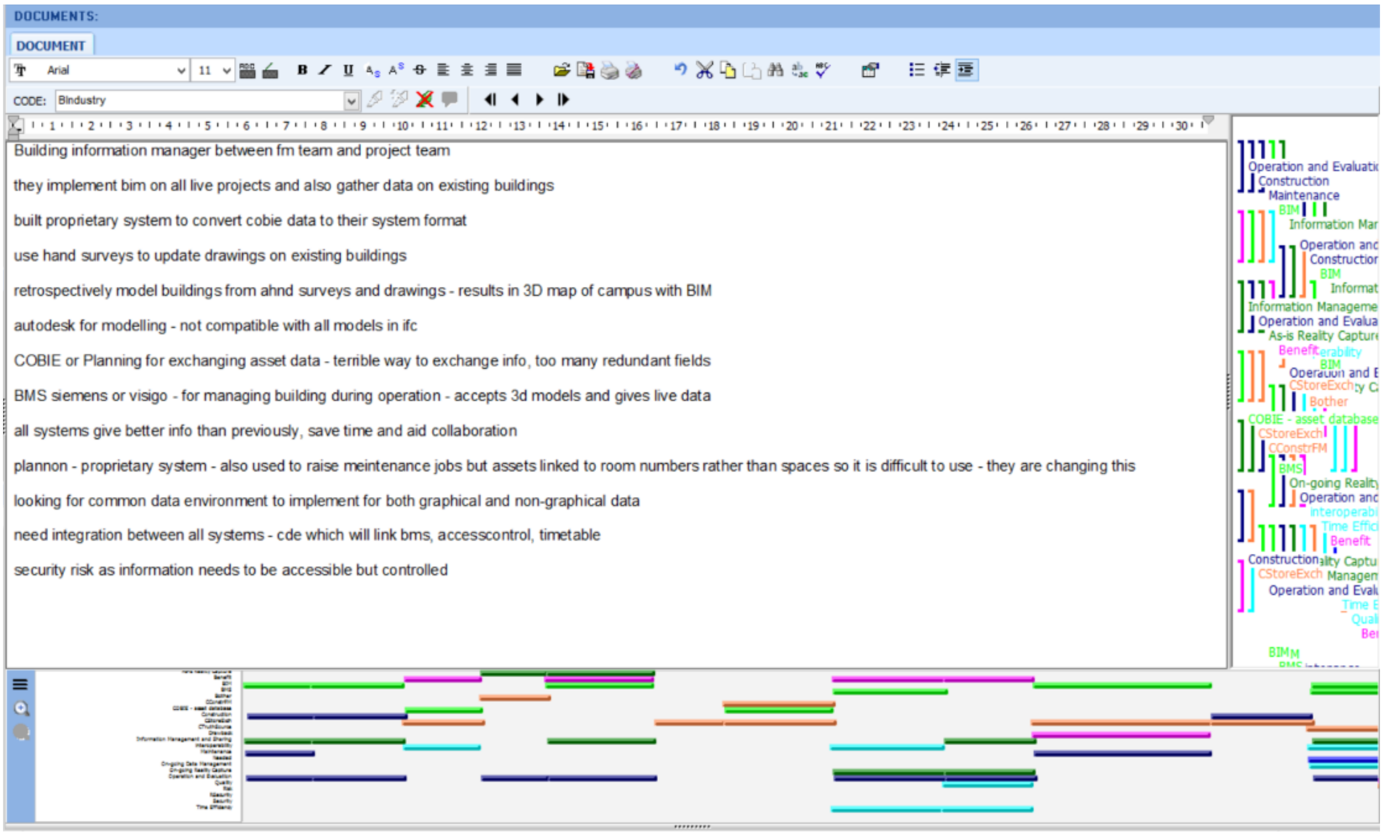


Figure 3-1: Screenshot of coding procedure used for interview notes

3.3 Results and Discussion

The following section outlines the results from the interview analysis, which was a main form of primary data capture, alongside the expert panel (discussed in Section 4) within this study.

3.3.1 Map of Current Digital Technology Use

Interviews were used to understand the current use and efficacy of digital technologies and at what point of the process (life-cycle) they tended to be used. These discussions have been interpreted by the research team to create a map of current technologies which highlights where a particular technology tends to be well used; when is it useful but has problems and when the technology is currently limited but industry would like to use is (see Figure 3-2). For example, BIM tools are currently well used for the design and construction of buildings (indicated by green on the technology map) but then in the operation and maintenance phase their use is currently limited (indicated by red on the map) due to issues such as interoperability.

The map clearly shows that although there are several technologies of “good efficacy” during the design, planning and construction stages, there are no technologies currently used in maintenance and deconstruction with “good efficacy”. In addition, while many of these technologies are used through several life-stages, they all vary in efficacy across life-stages.

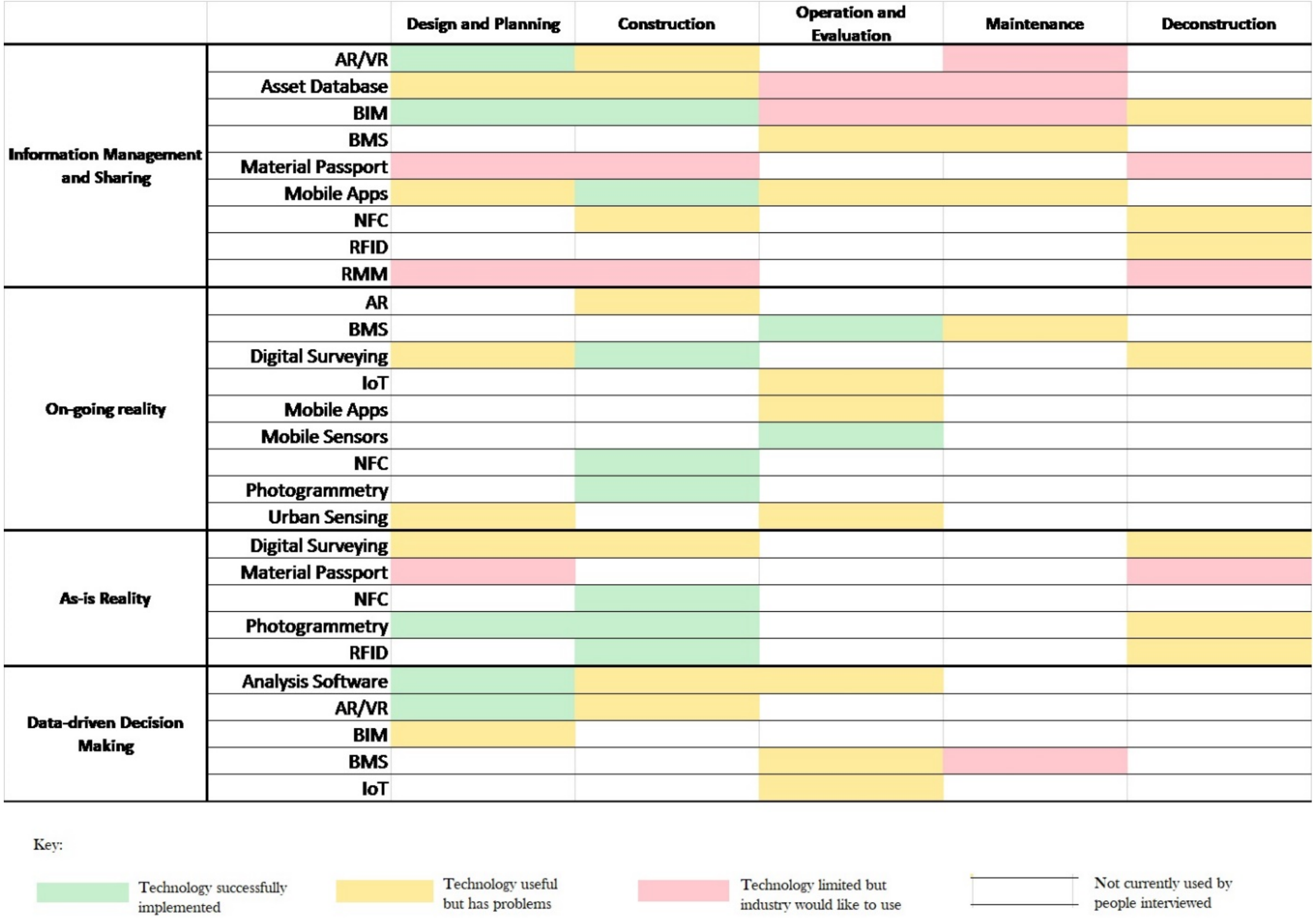


Figure 3-2: Map of current digital technology use

3.3.2 Capabilities (Opportunities and Needs)

During the interviews, a range of capabilities were identified sitting within the themes outlined in Section 1: As-is reality capture; On-going reality capture; Information management and sharing; and Data driven decision making. Through the analysis, the importance of the capabilities to those interviews has been interpreted (see Table 3-3). Some have been interpreted as important to a range of disciplines because they were discussed in detail by a range of different specialities; others have been interpreted as important to a specific discipline as detailed discussions tended to be from the one perspective; for others there was a general awareness of the capability but they were not discussed in depth and for some they were interpreted as capabilities whilst people were discussing barriers/risks. The following section provides examples of opportunities and needs discussed during the interviews. Recommendations and comparison to the literature review is provided in Section 6.

Table 3-3: Capabilities identified during interviews

Overall capability theme	Capability	Interpreted as:			
		range of disciplines	specific discipline	general awareness	from barriers/ris
As-is reality capture	Processing point cloud data			Y	
	Surveying hidden services		Y		
On-going reality capture	Occupancy data capture		Y		
	Building performance data capture			Y	
Management and sharing	Data storage and data exchange - interoperability	Y			
	Transfer of information from construction stage to operation stage	Y			
	Capturing and communicating uncertainty				Y
	Sharing data across the industry	Y			
	Management of building stock data			Y	
	Keeping an up to date model and creating a single source of truth	Y			

Overall capability theme	Capability	Interpreted as:			
		range of disciplines	specific discipline	general awareness	from barriers/ris
Data-driven decision making	Building optimisation during design				Y
	Holistic optimisation during operation		Y		
	Managing waste and extracting end of life value			Y	

As-is reality capture

Three capability categories were identified from the interviews sitting within the As-is reality capture research theme: processing point cloud data; checking installation during construction; and surveying hidden services. There was a general awareness and consensus that the technology exists to process point cloud data but it is not currently adequate to meet practitioners' needs. Reasons for this included: changes between the design and as-built models are not recorded by the contractors; there is a need to obtain semantically rich and more complete information cheaply; and need to frame point-clouds which are currently data-heavy.

A topic which appeared more dominant within conversations and has been interpreted as important to the construction industry, in particular contractors, is the need to check/verify installation during construction. Digital technologies such as augmented reality can be used to verify the location of components during construction and technologies such as photogrammetry can be used for progress checking and asset tagging. There is a need for this checking to mitigate risk by reducing remediating work and enhancing programme management. Although uptake is intended, interviewees were in general agreement that the technologies are not currently satisfactory in terms of the cost and benefit.

In terms of existing buildings, when surveying, a need identified was to gain an understanding of what is underneath the surfaces through under-surface scanning. This will help assist with projects such as 'Buildings as Material Banks' (BAMB) (Rose and Stegemann, 2018), which one of our interviewees works on. The aim of the BAMB project is to better understand buildings' components, whilst the technology is also beneficial in planning refurbishment schemes as this data capture could help reduce rework/risk by increasing the accuracy of technical feasibility studies. This captured information can also be useful at the deconstruction phase to identify end-of-life value in terms of the materials.

On-going reality capture

Occupancy data-capture and building performance data capture were capabilities within the On-going reality capture research theme. Interviews identified that when people occupy a property, changes to the building are often not recorded or digitalised. During the interviews, commercial property agents expressed that if occupancy data-capture is improved, it has the potential to help landlords better understand their client needs and add value to their property. Alongside this, there is a need to understand how people perceive physical changes to an internal environment, e.g. whether temperature changes are considered satisfactory.

Interviewees expressed frustration that building management systems are often there just for the sake of it and they are not well maintained and contain 'patchy' data, there were interoperability issues with sensors and although data is produced, it is often not used. Rather than putting new systems into existing buildings, some interviewees suggested using existing data streams such as CCTV or access systems, to answer the same occupancy questions.

Information management and sharing

Compared to the previous two themes, the Information management and sharing theme produced more capabilities, including: data storage and data exchange; transfer of information from construction stage to operation stage; capturing and communicating uncertainty; sharing data across the industry; management of building stock data; and keeping an up-to-date model and creating a single source of truth.

The data storage and exchange category has been interpreted as particularly important and was a capability regularly referred to across interviews. Firstly, there is a need to better integrate design and modelling for geometrically complex buildings, such as a need for 'craft' representation. This, in addition, captures a need for integration of parametric modelling with geometrically complex models. For instance, an architect discussed the use of bespoke carpentry in heritage buildings and how these components are often not included as standardised parts in BIM models. Secondly, there is currently limited integration between different building systems. For instance, it is difficult to integrate an asset database or inspection documentation with BIM models. Even within the same BIM software, an example was provided where the software has an energy analysis tool but cannot use that software if the model had not been built specifically for that purpose. It was suggested that general integration of systems (not specifically BIM) could be achieved through common data environments (CDEs) which contain building management systems, access systems and timetables. Currently companies are required to code their own conversions between certain software packages if they want them to communication or be interoperable.

The interviews indicated that there is a need for commissioning tools which will assist with the transfer of data from construction to facilities management (FM). Commissioning tools help with getting systems to function, do the diagnostics and outline how this has all been set up. These tools are currently in their infancy and require lots of rework of the data to create a written document that the Facilities Manager can use. Another example given to assist with the transfer of data is the importance of understanding the client's needs early in the process. During one interview an example was provided where a contractor 'walked' a facilities manager through a digital building model to discuss the feasibility of operation. This would assist in the future management of the building and understanding of information within the model when it is passed on.

Two types of uncertainty were identified during the interviews often indirectly through a discussion of risk, such as trusting the data. Firstly, if the data was collected a long time ago, there is concern over whether it is still applicable now. Secondly, the reasons for data collection often differ, so practitioners are concerned whether it is still applicable if using it for their own needs. An example was provided where a quantity surveyor could not use an architect's BIM model to quantify materials as the level of accuracy required had not been inputted by the architects and led to uncertainty when costing the work.

There was a general consensus across interviews that there is a benefit to sharing data and that industry should collaborate to increase progress rates, rather than different companies spending time and money developing the same things. Due to the smaller size of some companies, some interviewees considered it beneficial for them to partner up with larger companies as they do not have the resources required to analyse the data or develop the technologies themselves.

In terms of the management of building stock data, discussions indicated that there are few documentation systems that allow for whole estates to be managed as a single entity. This means each building has to be managed separately. This has created a need to improve the document repository for managing whole estates or asset portfolios.

Interview participants indicated the need to keep an up-to-date model as a single source of truth. Aspects related to this included the need to bring trade contractors into digital systems which help to compile one consistent building record for the hand-over stage, as well as a need for a better integrated information platform which includes documentation, models, schedules and scope of service all in one location (a single source). This should be the role of construction workers and maintenance teams rather than an additional office task.

Data-driven decision-making

Three capability categories were identified within the Data-driven decision-making research theme: optimisation during design; holistic optimisation during operation and managing waste and extracting end-of-life value.

For the optimisation of design people discussed parametric modelling. Rather than assessing the best of three options, digital tools could be developed to find an optimal solution through an automated process. This links with the other capability regarding the sharing of data as this will be beneficial in showing how buildings actually function, which can inform future design and decision-making. The design can also be optimised by using systems which can deal with complex projects and reduce repetition, this will assist in the uptake of new ideas and theories. A desire to quantity the benefits from technology in previous projects was also identified as this can help inform future decision-making.

To optimise a building during operation, an example included the use of control systems and how they need to be less top-down and more bottom-up. These could include self-learning algorithms which understand how humans interact with controls. In addition, it is important for the building users to be able to make decisions regarding their environment. Although current systems are capable of being adjusted, often only facility mangers understand the interface. The interface is often too complex for building users and interviewees felt there was a need to make these simpler. Holistic thinking is required as the points of interaction with the system need to be identified. An example was provided of how occupancy data could be captured through developing a digital building community, where people in the same building could report a problem and another member of that community may be able to help fix that problem. This will allow the building to be experienced as a service, rather than just a physical space.

In the context of managing waste, examples included a need to automate the sorting of construction waste for value recovery and that the end-of-life could benefit from material passports and trading platforms. An example was provided whereby shared transport could be used to make the recycling of specialist items more viable, as in some situations it is cheaper to send these items to landfill and pay the required tax. A quantity surveyor commented that there has been an increase in awareness of waste disposal techniques and deconstruction over the past five years.

3.3.3 Risks

Creating systems that become redundant quickly or are outdated; privacy; security; the unskilled use of technology; and oversimplifying/overcomplicating data were all risks of digital tool implementation that were identified during the interviews. In some cases these were explicitly referred to when the interviewee was asked what they thought the major risks were when implementing digital tools, in others they emerged as risks when the interviewee was discussing a specific technology.

Discussions indicated that systems can become redundant for three main reasons: practitioners cannot ensure that the technology set out at the start of a project is still relevant through the whole life of a building; there is often an inconsistent data format; and people are often waiting to see what the next advance of a digital technology is, which makes them hesitant to invest in a technology which will be superseded.

Although privacy was mentioned by a few interviewees, preventing them from sharing data because of privacy concerns and the potential for a conflict of interest over data ownership, there was a stronger focus on the security of data. This included the physical security of a building or large piece of infrastructure being compromised and well as the security of the data itself. A key concern expressed was the risk of cyber-attacks and compromises to data protection, which included the potential loss of Intellectual Property.

Although technology may exist and function appropriately when used properly, interviewees referred to examples when the technology was used by people who were unskilled, which led to the digital tool becoming a problem rather than a benefit. For instance, there may be 'black boxes' as people use the models without fully understanding them or they may take a blanket approach to applying a technology which can mislead implementation. This can be costly in both time and money.

Additionally, there are examples where people referred to the risk of over simplifying data/models or over complicating them. Although these are opposites, both lead to difficulties in digital tool implementation. If oversimplified, aspects of the tool may be ignored, and/or important bits of information may be lost. For instance, when a surveyor assesses a property, if recording the geometries, they will often note if a particular component is in poor condition. If point-cloud data is used, it is likely this will be overlooked and only geometry recorded. In terms of over complicating, this relates to when people are required to collect or input data that they do not need to carry out a job. If a job is 'small and fast', then the monetary cost and time of making a digital model is not seen as beneficial. For example, if a BIM model currently does not exist for a building and the furniture within an office is replaced, a BIM model is not required.

3.3.4 Barriers

A range of barriers to the implementation of digital tools was identified in the interviews including: trust of people/commitment/responsibility for accuracy; cost (technology, training); ownership of data (access); FM buy-in/skills; and industry structure and status quo. As with risks, some barriers were explicitly referred to and others have been interpreted from the conversation.

The accuracy of BIM models was questioned by some interviewees as they felt that people using them often have different aims and there can be a lack of trust in someone else's inputs. In the context of uncertainty (see Section 3.3.2) an example was provided whereby an architect's BIM model is often not appropriate to use for assessing quantities by a QS. Due to the different aims of the model's users, often people only care about the aspects which are relevant to them.

The cost of technology and the training of people which is required to use them were identified as a barrier to digital uptake, especially for small companies in construction. The size of companies is important to note, as 96% of construction firms in England have fewer than 13 employees[1]. According to one interviewee, in general people are usually looking for a payback of 2-3 years through the operation costs for the investment in digital tools. In terms of maintenance, the same parts of the building still need to be replaced so the cost saving is in the management time which is a smaller budget, hence less of a financial incentive.

A further barrier identified is the ownership of data. Although there is a need identified to share data, interviewees referred to legal issues over who owns or controls models, which discourages collaboration and learning between the different disciplines. Sometimes collaboration is hindered as people cannot access information due to these ownership issues.

A regularly referred to barrier was issues brought about by the lack of incentives for construction and maintenance workers to record information and keep BIM models up to date. This is because they are often not paid for the additional work; do not own the data and the data collection is of no benefit to them. The extra effort does not actually lead to extra pay and interviewees indicated this would require a restructuring of industry roles. It was suggested the current system is siloed/layered, which can act as a barrier. For example, a maintenance contractor on an existing contract has no incentive to invest in new technologies. This links to the status quo of industry, which was defined as a barrier. Two aspects associated with this include the tendency to go with the lowest cost, not necessarily the best value and those who are leaders in digital technology not necessarily making the decisions on companies' digital strategies. Often the people for whom digital technology is intuitive do not sit in leadership roles. Those making decisions have vast amounts of experience in the industry but do not have the relevant training in digital tools to have an in-depth understanding of their benefits and how they can be used.

3.3.5 Effective Enablers

Having incentives and proof of technology benefits were two effective enablers identified. Incentives can include direct financial incentives, such as funding which will encourage stakeholders to use a technology, but can also include indirect financial incentives, including becoming recognised as an industry leader by working on a research project using a specific tool. This can help to promote the company as a front-runner. In some cases, this incentive may be a mandate, whereby certain digital tools are required on construction projects. For

[1] Statistic referred to during interview. Source identified as 'UK: Construction firms by size in England in the third quarter 2016' - https://www.statista.com/statistics/564797/construction-firms-size-region-england/

instance, it was suggested that the uptake of BIM Level 2 had increased as companies were mandating it themselves following the requirement to use it on centrally funded public projects.

Due to the cost barrier associated with digital technologies' uptake, interviewees felt that people needed to better understand the benefits and this could be achieved through a proof-of-benefits, which includes the promotion of successful case studies.

3.3.6 Attitudes

During discussions there were examples where the blame was put on specific roles within the process. In particular, the focus tended to be on the clients not clearly understanding what they need and features, such as those which will assist with the maintenance of a building, are not taken into account early enough. Differing purposes was defined as a barrier to the use of digital tools, which contribute to this misunderstanding of where responsibility lies. To overcome this, people need to think beyond their particular point in the process.

A feature of the current industry structure is that the construction/maintenance workers tend to be lower paid than people in other roles, such as facilities managers. Currently there is a lack of incentive for these workers to make the changes suggested on site as they are not paid for this additional work.

4 Expert Panel

4.1 Objectives

The expert panel session was used to elicit undocumented knowledge from academic and industry experts. This session complemented the interviews, allowing for cross-disciplinary discussion, identification of industry-wide needs and assessment of priorities. Within the context of the scope of the project, the specific objectives of the expert panel Session were as follows:

Objective 1: To validate/disprove/augment the 'capability needs' identified through the literature review, with an emphasis on the perspective of industry:

a) To understand what new capabilities are required
b) To understand the current specific barriers to the industry having this capability
c) To understand the risks of the new capability
d) To understand what type of organisation is best placed to address these issues

Objective 2: To understand industry priorities

Objective 3: To understand, more generally, what measures positively influence the adoption of new technologies.

4.2 Methodology

The expert panel meeting took place at Cripps Conference Centre at Magdalene College Cambridge on November 28th 2018. Invitations were sent to individuals from each of the following groups: building owners, architects, structural engineers, M&E engineers, quantity surveyors, contractors, facilities managers, industry guidance bodies, technology providers and some academics. Following personal invitations sent to around 40 experts, a total of 26 people, including the CAR team, attended the meeting. The names of the experts and a brief summary of their roles are given in Appendix C. To make sure that the maximum value, in terms of capability definitions and prioritization, was achieved CAR recruited the services of an experienced workshop facilitator, Bengt Cousins-Jenvey from Useful Projects and Expedition Engineering.

The meeting began with a brief presentation about CDBB, its aims and programme, from Dr. Charles Boulton, followed by a presentation by Dr. Eleanor Voss and Bengt Cousins-Jenvey describing the research project context, scope and deliverables. This presentation included details of the purpose and format of the session, and how the outcomes of the session would contribute to the project.

The group then divided into four separate discussion groups, Groups A and B discussing the research theme As-is reality capture, and Groups C and D discussing the research theme On-going reality capture. These group discussions (Process 1 – to identify capabilities needed) were followed by a plenary session to define and prioritise the capabilities identified (Process 2). In the afternoon the group again divided into four discussion groups, with different membership from the morning groups. Groups 1 and 2 discussed the research theme of Information management and sharing, and Groups 3 and 4 discussed the research theme of Data-driven decision making, followed by a final plenary and prioritisation session. An on-line survey was also used to assemble responses to questions about the adoption of new technologies (Process 3). The details of how each of these three processes were organized are described below.

4.2.1 Process 1: Panel Discussions to Meet Objective 1

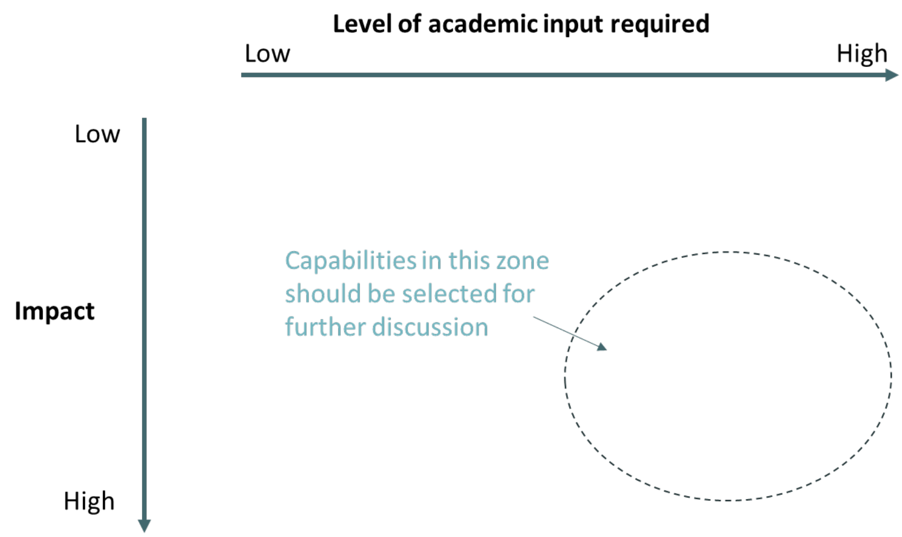
Each of the 4 groups had one of the CAR team as facilitator. The schedule to run the discussions was as follows:

Task	Time	Description
1	5 min	- Facilitator asks if the group would like to reintroduce themselves, re-iterates topic very briefly, lays out the plan for the session
2	5 mins	Define how capabilities will be selected The facilitator encourages the group decide as a group how they will define impact - The facilitator says that three definitions of impact are available: 1. Environmental Value 2. Social Value 3. Economic Value (increased productivity/reduced costs) - The group should then decide how they will rank these – all the same?
3	5 mins	Identify required capabilities - As individuals, each group member thinks of 2-3 ways to complete the following sentence: '*We need to know how to YYYY*' and writes them on post-it notes (one capability per post-it)
4	15 mins	Select capabilities - The facilitator draws the 'Selection Chart' on the flip chart. - The group aims to place the capabilities on the chart. - Each group member reads out a capability that they have identified briefly to catch any duplicates - Through discussion, the group agrees where to place them on chart. - The group can add more capabilities on post-it to the chart if they think of them.

		- The facilitator takes notes of this discussion for use later in the discussion session and for processing - The 2-3 capabilities that have been identified as most impactful, and most in need of research input are selected for further discussion.
5	25 mins	Understand capabilities - For each of the 2-3 selected capabilities, one 'Capabilities Table' template should be filled in. - The facilitator is responsible for filling in the table, based on the consensus reached by the group. - The facilitator should use the notes taken in task 4 to speed up the process.
6	5 mins	Prepare for Plenary - Make the posters using poster template. One poster per capability. Choose a spokesperson, who will present the information on the Capabilities Posters.

To select capabilities for further discussion, a means to establish the most important was needed. We were looking to define those which had both high impact and high research input; and these are likely to be the ones for which our current understanding is most lacking. This was identified by using the selection axis shown on the diagram below. However, those with high impact and low research are still interesting and these are presented in Appendix D.

Selection Axis



Capabilities Table (one completed for each of the three top capabilities identified)

1	Complete this sentence: 'We need to know how to YYYY'	
2	Which life-cycle stage does this address? (Planning, Design, Construction, Operation, Maintenance, Deconstruction)	
3	Why do you need to know how to do YYYY?	
4	What is stopping you doing YYYY?	
5	What are the risks of doing YYYY that will require mitigation?	
6	Other than researchers, who is best placed to make it possible to do YYYY? (government, institutions, technology providers, standards developers	

Poster Template (one to be completed for each of the three top capabilities identified)

We need to know how to ……	
We need to know how to do YYYY because ….	

Facilitators were given advice on avoiding problems in managing the discussion.

4.2.2 Process 2: Plenaries to Meet Objective 2

The facilitator for the plenary sessions was Bengt Cousins-Jenvey. The schedule for each plenary was as follows.

Task	**Time**	**Description**
1	5 mins	Brief re-introduction to process
2	Allow 30 mins	- Each of the four groups presents 2-3 capabilities - They spend 2 minutes on each capability - The posters are pinned on a wall
3	5 mins	- At the end of the presentations, whilst still sitting down, the experts are asked to choose their top three priorities within each theme i.e. six items per plenary. - Write the group and capability identifier (1,2,3) on the post-its (top: hot pink; middle: orange; bottom: yellow) i.e. ending up with six post-its - The project team then help the experts put their post-it notes under the appropriate posters.
4	5 mins	Sum up from facilitator In the second plenary session, the facilitator requests a show of hands to identify the prioritisation of the four different research themes.
5	Immediately after	- Wall is photographed - Numbers of post-its recorded

4.2.3 Process 3: Survey on Measures that Encourage Technology Adoption

A digital survey was set up using Survey Monkey and was available throughout the day, providing a live tracking/ presentation of results.

Participants were asked to identify two primary examples with 3 questions for each.

Example 1: Think of a recent example where you adopted a new technology:

1. What was the technology?
2. What encouraged you to adopt it? (Options: case study, cost benefit analysis, you spoke with someone who already had, government policy, client requirement, ...other?)
3. Why did this make you adopt the new technology?

Example 2: Think of a recent example where you are aware of a relevant technology, but you have not adopted it:

1. What is the technology?
2. Why haven't you adopted it?
3. What would need to change for you to adopt it?

4.3 Results and Discussion

The results presented are derived primarily from the detailed Capability Tables developed by each group, and then subsequently prioritised in the plenary session (Tables 4-2 to 4-5). This means that the capabilities discussed below are those for which both high impact and also significant research needs were identified. A few of those for which high impact but low research needs were identified are also discussed in Section 4.3.6.

It is convenient, for presentation and discussion, to divide the capabilities between the overall research themes derived from the literature review and used to form the discussion groups at the plenary workshop (Section 4.2). The full list of capabilities identified in the workshop, and their associated research themes and categories, are shown in Appendix D.

Table 4-1: Capabilities by research theme and prioritisation

	Number of identified capabilities	Vote
As-is reality capture	3	3
On-going reality capture	6	2
Information management and sharing	11	11
Data-driven decision making	3	4

Table 4-1 shows the breakdown of the prioritised capabilities by research theme. The research theme Information management and sharing constituted the largest number of capabilities (11) presented in the plenary sessions. This high number is consistent with the voting which took place in the final plenary to identify which of the four research themes should be given priority, at which 11 of the 20 participants identified this theme (Table 4-1). A further 6 of the capabilities related to the theme of On-going reality capture, 3 for As-is reality capture, and 3 for Data-driven decision-making (though these included 2 which were also identified in the On-going reality capture theme).

This ranking suggests that the expert-practitioner group who attended the workshop believe that information management and sharing is the most important aspect of digital tools requiring further development.

Table 4-2 toTable 4-5 show the information gathered about the proposed high impact, high research input capabilities in the Capability Tables described above in Section 4.2.1, for each of the four research themes. They also show the prioritisation of each capability given by the whole panel. The prioritisation score shown is derived from the preferences for each individual capability expressed in the two plenary sessions. The score is derived from the number of first, second and third preferences expressed for each (3 points for first, 2 for second and 1 for third priority), and has a maximum of 60 (if all panel participants gave it their first preference). It is important to note, however that the prioritisation was carried out between the capability categories belonging to each research theme separately. Only the overall vote in Table 4-1: Capabilities by research theme and prioritisation allows us to judge the overall priority given to each research theme. The information obtained from the discussion groups and tables is summarised below for each of the four research themes.

Table 4-2: Capabilities identified relating to research theme As-is Reality Capture

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	What are the risks?	Other than researchers, who needs to contribute?
B.1	A1		B1	19	2	automated and fast/real time process to convert point cloud data to reliable intelligent model and have commitment (legal) for its reliability	all	for it to form a reliable and easily useable data source	technology gap; poor understanding of what is needed in the intelligent model	overloaded model is difficult to handle; contracts needed to manage risk of the reliability of the model generated	technology providers; institutions to create suitable contracts
A.2	A2 and O2		B2	45	1=	collect as-built data about fabric and services in existing buildings	All	in order to manage risk; make better decisions; increase efficiency	Expensive; Time-consuming; Intrusive methods problematic	None identified	building owners (who also operate the buildings); BIM requirements
B.2	A2		B3, B5	45	1=	Capture data about the asset that is hidden (below ground, behind walls) but in an unobtrusive way and have legal commitment to allow other project members to treat it as reliable.	all	in order to avoid loss of rental income when planning renovation works; H&S; avoid damage to unknown services; avoid having to be over conservative in avoiding services when location is not known exactly	technology is insufficient; commitment on reliability of information; given cost-benefit information available to clients (if any), they don't agree to use advanced technologies that do exist	having information but no confidence on reliability/ legal commitment of accuracy means that the data would not be useful or can lead to duplicative work as each party confirms accuracy to their satisfaction; data can be open to misinterpretation; too much data can be difficult to handle - it must be the right data to the right level of detail	industry institutions; government/ regulator; technology providers

Table 4-3: Capabilities identified relating to research theme On-going Reality Capture

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	what are the risks?	Other than researchers, who needs to contribute?
C.1	O1 and D2	R2	B1	24	5	optimise occupancy	all except deconstruction	to learn from existing process, to increase comfort and well-being, to increase energy efficiency; to increase productivity	lack of understanding between experiential and physical, quality of current experiential feedback	data privacy, misunderstanding or desires, people won't share data or people won't give honest feedback	end-users; other expertise such as psychologists
1.1	O1 and D2	R2, R3	B3	21	6	Integrate occupancy performance data with the rest of the asset data. i.e. are the occupants/workers achieving the productivity levels envisaged?	planning and design	to understand if the business case is being delivered on	data not available or not captured in the first place; cultural silo between design/operation	privacy of data; security of dynamic data	client groups (e.g. Association of University Estate Directors)
A.1	O2		B1, B3	30	4	prioritise and apply cost-benefit evaluation to alternative data collection exercises	Planning, design, maintenance	Avoid collecting redundant data. Ensure data collected is useful.	Weak connection between people specifying data collection and people using data at later stages; no market for data that would lead to efficient decisions	Risk of collecting too little data	Government Standards

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	what are the risks?	Other than researchers, who needs to contribute?
A.2	O2 (and A2)		B2	45	1	collect as-built data about fabric and services in existing buildings	All	to manage risk; make better decisions; improve efficiency	Expensive; Time-consuming; Intrusive methods problematic	None identified	Building owners (who also operate the buildings) BIM requirements
D.1	O2	R3	B3, B5	33	3	have material passports and log-books for buildings	Design; Operation and Maintenance	Changes to a building are currently difficult to capture e.g. the lifespan of fire door seal. Every few months something changes in a building/	no economic incentive; not regulated; value engineering destroys value; lack of communication and central system	Resistance to new regulations is a barrier; unified desire; cyber security e.g. Hacking sensor data	Need case studies; need to prove financial impact; example of how data can be used for other means e.g. police could use information about buildings in emergency situation

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in theme	We need to know how to….	Which life-cycle stage?	Why do you need to know how to…?	What is stopping you doing …?	what are the risks?	Other than researchers, who needs to contribute?
D.2	O2		B3	35	2	develop business model to understand space as a service	All	to classify construction as a service; people currently trying to do this without the data; need to migrate from the capital phase; scenarios which describe what would be possible	Accuracy and lack of data - people benefit from not distributing ; block chains; uncertainty of change	Brexit - financial world and instability (link to business rates)	Manufacturers as market competitors

Table 4-4: Capabilities identified relating to research theme Information Management and Sharing

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	what are the risks?	Other than researchers, who needs to contribute?
1.2	IM2		B1, B3	21	8	effectively transfer data from design/construction stages to the FM team	construction - operation	to improve return on investment in BIM i.e. better cost/benefit ratio for clients; reduce re-work; avoid loss of information	Technology is insufficient, data exchange formats are not reliable		Standards developers
4.1	IM1		B1, B3	20	9	standardise data requirements (attributes), especially for materials	all	to prioritise decision-making attributes – e.g. noise/acoustic performance	Too many parties involved. Naming conventions also differ between stakeholders.	That you cannot standardise data sufficiently. That products change. Standardisation does not really work for existing buildings.	Government, Members of Professional Institutions, Standards Bodies (like BSI)
A.3	IM1	R1	B3	30	4	ensure compatibility of data, e.g. by data exchange formats	design, construction, operation	to maximise benefit from data that has been collected Efficiency	Data ownership/IP; Diversity of non-compatible systems; Technical difficulty of setting standards	Undermine viability of data-providing businesses Locking-in to current technology that will become obsolete	Technology providers Industry initiatives

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	what are the risks?	Other than researchers, who needs to contribute?
3.1	IM4		B1	27	5=	trust the data	All	to contextualise the data e.g. how produced and why; understanding abnormalities	High number of parameters and volume of data; uncertainty		Standards bodies; planning process
1.3	IM4	R2	B3	9	10	Have data available to be able to draw out lessons learnt	design operation	continual cycles of improvement	no centralised database data ownership/willingness to share	data privacy; lack of data curation i.e. too much data could be a hindrance	government
2.1	IM1		B3,B4	27	5=	communicate effectively between different software tools and disciplines	all	to save time, to gain transparency on processes, to increase productivity	silo culture of built environment, fragmented workflow, software processes, legacy systems, lack of standards on things such as an industry programming language	choosing the wrong standard, stifling innovation by being too prescriptive, coalition of capabilities leading to non-distinct roles, where does the cost/time to make it happen come from?	industry bodies for standards, govt for legislation, software developers, practitioners

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in the theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	what are the risks?	Other than researchers, who needs to contribute?
2.2	IM4	R2	B1, B3, B5	47	1	share data in a valuable and risk-balanced way	all	to improve access to datasets, to optimise the built environment for multiple benefits	fear/uncertainty/doubt of what will happen to data, red-tape, lack of contractual frameworks for data sharing, lack of awareness of benefits to companies if they share data	privacy, legal liability	govt, industry bodies, and crucially everyone with data to contribute
3.2	IM4	R2, R3	B3	31	3	understand existing data	All (perhaps more operation to inform future design)	to better inform future design; learn how to shape future data; access to raw data would allow consultants to do what they wanted with it, rather than passing on clustered data	people don't like sharing data e.g. cost consultants; data is currently very fragmented (no one has confidence to bring it all together); don't know what data is needed	Privacy; perceived risk of terrorist attacks; uncertainty in data; may lead to unexpected outcomes	People outside the construction sector used to dealing with big data

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in the theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	what are the risks?	Other than researchers, who needs to contribute?
4.1	IM4		B3	23	7	Introduce a feedback loop – especially from failures	Planning-design-construction-maintenance	to stop repeating the same mistakes, and to improve efficiency	Risk of liability claims; reputation damage; IP; no space/forum to do this	Identifying those who made mistakes, and reprisals. Platitudes (only recording the positive, or avoiding the biggest failings).	Whole construction industry, professional institutions
C.2	IM6		B5	32	2	make building information accessible and useful throughout lifecycle	all	to reduce waste across the board (time, cost, resource) - lean principles	existing contractual requirements; lack of skills; lack of optimised use case to prove value	misunderstanding of other stakeholder needs	companies doing pilot projects, industry to input on what information is useful, standards bodies to introduce codes as to what should be modelled and how

Table 4-5: Capabilities identified relating to research theme Data-driven Decision Making

Capability number	Capability category	Risk category	Barrier category	Score	Prioritisation in theme	We need to know how to....	Which life-cycle stage?	Why do you need to know how to...?	What is stopping you doing ...?	What are the risks?	Other than researchers, who needs to contribute?
4.2	D1		B1, B3	26	1	Quantify unquantified data so they are included in design decision making	Planning, design, operation	so that not just the money is considered in design decisions	Too many parties involved. Naming conventions also differ between stakeholders: no centralised database data ownership/willingness to share	That we end up over-simplifying. Also that we lose nuances from different opinions and perspectives.	Consultants, especially architects (who are good at emphasizing un-quantified aspects, like landscaping)
C.1	O1 and D2	R2	B1	24	2	optimise occupancy	all except deconstruct ion	to learn from existing process, to increase comfort and well-being, to increase energy efficiency, to increase productivity	lack of understanding between experiential and physical, quality of current experiential feedback	data privacy, misunderstandi ng or desires, people won't share data or people won't give honest feedback	end-users, other expertise such as psychologists
1.1	01 and D2	R2, R3	B3	21	3	Integrate occupancy performance data with the rest of the asset data. i.e. are the occupants/workers achieving the productivity levels envisaged?	planning and design	to understand if the business case is being delivered on	data not available or not captured in the first place; cultural silo between design/operation	privacy of data; security of dynamic data	client groups (e.g. Association of University Estate Directors)

4.3.1 As-is Reality Capture

Two separate aspects of As-is reality capture have been identified in Table 4-2, namely processing of point cloud survey data and surveying hidden services. Each of these aspects was represented in one of the capabilities identified. One capability proposed was "to achieve an automated and rapid process to convert point-cloud data into a reliable intelligent building model, with a contractual commitment for its reliability". This is seen as a key step to creating digital twins for existing buildings. Current barriers to achieving this are a technology gap, as well as poor communication of what is needed in an intelligent model. Risks are those associated with the liability of the provider for subsequent use of the model generated.

A second proposed capability in this theme is to find a way to "capture hidden data (below ground or behind walls) in existing buildings, but in a manner which is unobtrusive to current occupation of the building". It is seen as important, as in the above example, for the provider to have a contractual commitment for its reliability. The aims would be to avoid damage to existing below ground services while also avoiding loss of rental income in planning renovations. Perceived barriers are lack of suitably developed technology, but also the liability which the technology provider would be taking on associated with the uncertainty of the data provided.

4.3.2 On-going Reality Capture

Two separate aspects of On-going reality capture have been distinguished (Table 4-3), namely building performance data capture (energy use, environmental performance etc) and occupancy data capture (including both interaction of occupants with the building's operational tools and productivity/user satisfaction). Among the six capabilities identified at the Panel, four related to building performance, and only two to occupancy data. Capabilities identified related to occupancy were to "optimise occupancy" and to "integrate occupancy performance data with the rest of the asset data". The aims were to increase occupant comfort and well-being, increase energy efficiency, increase productivity, and understand if the building project is delivering what was intended. Barriers to achieving this were identified as a lack of occupant data being assembled, and an absence of adequate understanding of the interaction between buildings and their occupants. Risks identified were data privacy (especially regarding occupants) and associated data security.

Two of the capabilities identified related to building performance were to "collect as-built data about fabric and services in existing buildings", and to "have materials passports and log-books". Aims would be to chart changes in buildings through their lifetime for better management and improved efficiency. Barriers perceived were the current lack of any economic incentive for assembling such information, the cost, and the intrusive measures that might be needed. Risks identified included data security issues.

4.3.3 Information Management and Sharing

In the literature review, five different capability groups were identified within this research theme, of which four were represented here. The most common related to *Data storage and data exchange* (3) and *Capturing and sharing data across the industry (6).*

The capability needs identified under the heading *data storage and data exchange* were to "effectively transfer data from the design and construction stages to the facilities management team", to "standardise data requirements, especially for materials", to "ensure compatibility of data through data exchange formats". These would be aimed to maximise the utility of data collected, as well as improving the benefit gained from the cost of investment in the required technology. Perceived barriers were in terms of currently fragmented data ownership, and the diversity of alternative systems and their associated naming conventions. Risks identified were that of creating a system that would soon be outdated. Unsuitability of current systems for work on existing buildings was also noted.

The capability needs identified under *capturing and sharing data across the industry* inevitably have some overlap with the previous group. The most significant of these were to "make building information accessible and useful throughout the lifecycle", to "improve communication between disciplines and their different software tools", to "better understand the available data", to "create a way to learn lessons from failures" and to "trust the data". These capabilities would be aimed to inform future design, to gain transparency, and to reduce inefficiencies. Perceived barriers to achieving this which were identified were the issues of data ownership and willingness on the part of the owners to share it, lack of contractual frameworks for data sharing, as well as a lack of standards. The risks identified included liability claims and reputational damage as well as data privacy concerns, and concerns about data security.

4.3.4 Data-driven Decision Making

Data-driven decision-making was represented by 3 capabilities two of them overlapping with those discussed in the on-going reality capture category. The capability not discussed is "to quantify unquantified data so that they are able to be used in design decision-making" The aim would be to ensure that design decisions are able to take account of (especially) non-financial aspects. Barriers identified were that too many partners are involved, and that owners of relevant data are unwilling to share it; also that there is no centralised database of the information needed. A risk identified was that oversimplification could result from this approach

Although decision making did not attract many votes in the plenary session, there was vigorous debate in the panel session about the difficulties of prioritising competing pressures on the design process – especially when some pressures are hard to quantify (like social and some environmental issues). There was also discussion about how to balance different client priorities (cost, time, quality, aesthetics), particularly when these priorities are unvoiced and often only become clear towards the end of design, when key decisions are already made.

Participants in this session also identified difficulties ensuring that learning acquired on one project could be recorded and applied to other projects – not solely by the original project team. They saw a role here for additional research input.

4.3.5 Required Collaborators

A wide range of non-academic organisations were identified as making necessary contributions to delivering these capabilities. For the capabilities identified under As-is reality capture, the technology providers were of greatest importance, but also either industry or industry institutions to develop appropriate contracts. For the capabilities identified under On-going reality capture, it was the building owners and their facilities managers who were most commonly cited; but for building occupant behaviour issues, psychologists were identified. For the capabilities identified under information management and sharing, emphasis was placed on the need for involvement by industry-wide bodies, government and standards agencies to create the appropriate standards and protocols for data sharing. Reference was also made to the need for companies (designers, builders, facilities managers) undertaking pilot projects to feed back their experience for the benefit of others through case studies.

4.3.6 Overall Priorities

Three capabilities identified and prioritized by the entire panel emerged as having the highest priority score. One was Capability 2.2 "to share data in a valuable and risk-balanced way". Reasons given for needing this very broadly defined capability were that "datasets exist, but people either do not know about them, or cannot access them, so a lot of rework is occurring". Many benefits were seen to be available, both from a financial and environmental perspective, from a greater sharing of existing datasets, but this was seen to be heavily constrained by contractual issues and the perceived risks of data sharing.

A second was Capability A.2 which was defined as to "collect as-built data about fabric and services in existing buildings". This is also a very broadly defined capability, and spans both the research themes of as-built and on-going reality capture. Benefits were seen as better decisions, higher efficiency and managing risk, but constrained by costs, the time required, and the possibly intrusive methods needed.

A third priority was Capability B.2 to "capture data about the asset that is hidden (below-ground or behind walls) but in an unobtrusive way". The capability emphasises the need for the data obtained to be reliable, and for other project members to be able to trust it. The benefits were identified as avoiding loss of rental income, avoiding damage to unknown services, and avoiding being overly conservative in circumventing services whose location is unknown. Constraints identified were insufficiently well- developed technology and lack of contractual commitments on the accuracy of data available. A clear role both for technology providers and for industry bodies to develop better contractual tools was identified.

It is important to note though that these three capabilities are those given top priority in discussions on three separate research themes. Their relative priority, and their priority in relation to capabilities in different research themes is thus unknown.

A number of capabilities were identified in the separate panel discussions which were not presented to the plenary discussion because, although they were thought to have high impact, they did not have a correspondingly high research need. The table in Appendix D lists all of the capabilities put forward in the separate panel discussions and gives also the score (on a scale of 1 to 5) against "impact" and "research needed". These capabilities were not explored in the plenary, but those with high impact but low research needed might be seen as "low-hanging fruit" which the industry could adopt relatively quickly. These included "bring structure to unstructured data by implementing industry naming conventions for assets" and "effectively share modelling data to avoid rework, including programming interfaces and access permissions issues". A third such example was to "use modelling and simulation to inform decisions (foreseeing outcomes of decisions at an early stage)". These capabilities are in some respects emphasizing the more easily adoptable aspects of some of the highest priority capabilities previously identified. Both industry sharing and some research at the level of case studies could be of value in facilitating their adoption.

4.3.7 Panellists' Definition of Impact

Each discussion group was asked to consider their collective definition of impact, in particular to choose whether they would give priority to impact in relation to the environmental value, social value or economic value of capabilities proposed. As would be expected, there were a variety of responses. In most cases it was agreed that each of these classes of impact should ideally be considered. However, it was commonly stated that social value tended to be overlooked, because it is difficult to measure, and also that financial pressure will tend to take priority over environmental and social impact. Enhancing productivity was a central concern, particularly for those involved in the construction process. Nevertheless, as pointed out by one group, environmental impact should be regarded as the primary impact, as nothing else will matter if the environment is not preserved; it was also noted that environmental impact is often quantified through economic incentives. These divergent views on the meaning of impact will all have had an effect on the prioritization of the capabilities expressed both within the separate groups and in the plenary sessions.

4.3.8 Effective Enablers

While the survey that formed Process 3 outlined in the methodology received only 12 responses, it is still possible to draw some useful conclusions. From the survey data, in Figure 4-1 and Figure 4-2, it is clear that cost-benefit analysis, personal recommendation and client requirement are all strong reasons for people taking up a new technology. The "other" category was also sizable, but the free text responses had no unifying theme. On the topic of reasons for not taking up a new technology (Figure 4-2), cost-benefit analysis, uncertainty on return on investment, and lack of necessary skills for implementation all featured strongly.

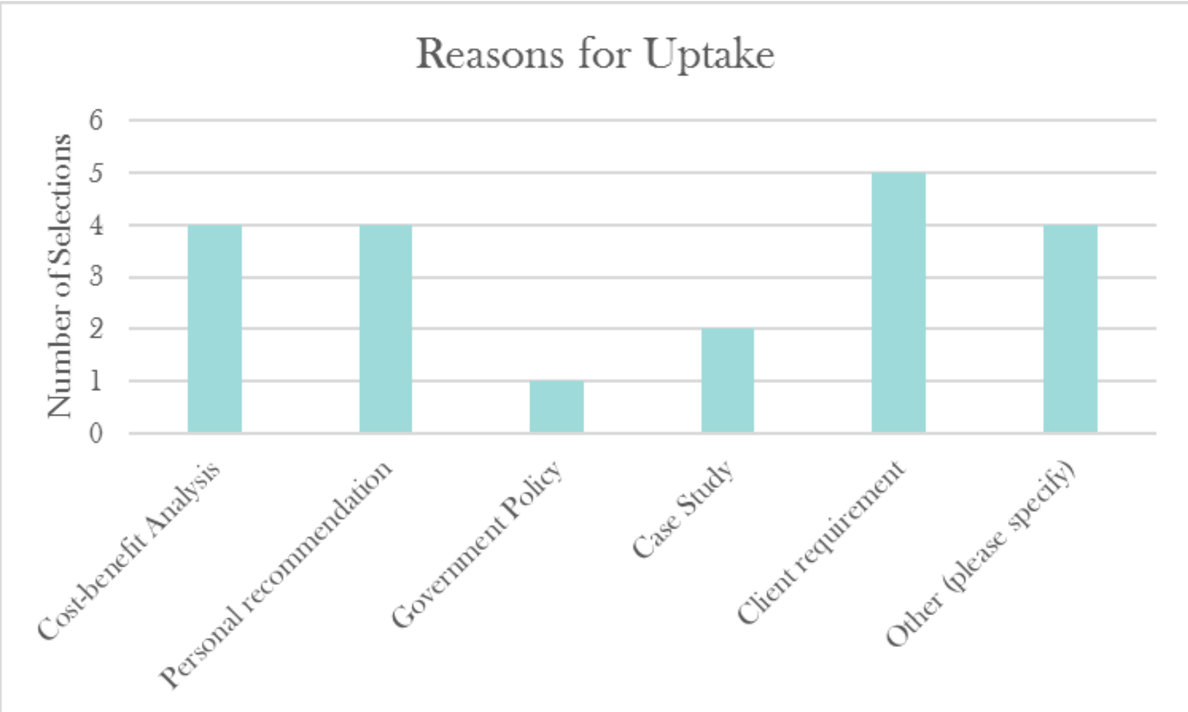


Figure 4-1: Technology enablers: reasons for uptake identified in the survey

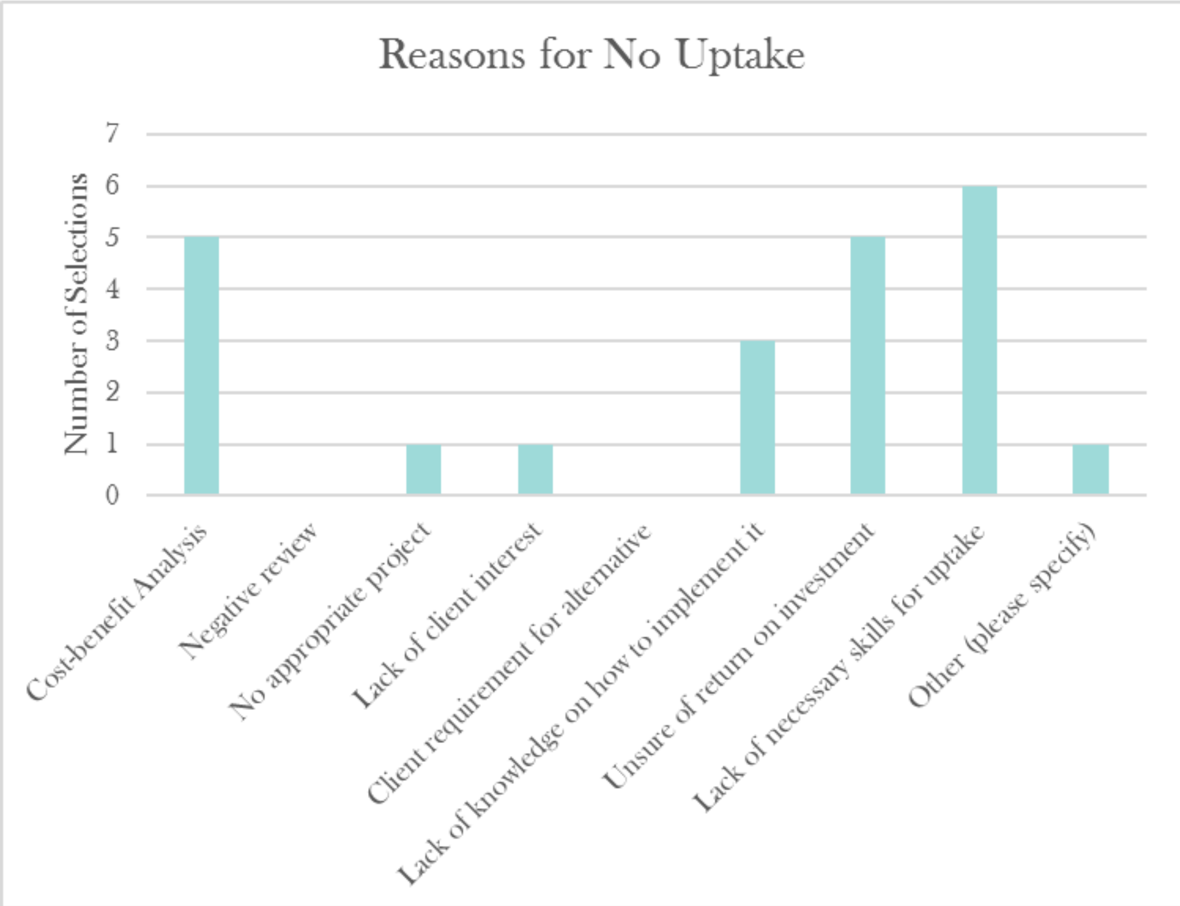


Figure 4-2: Technology enablers: barriers to uptake identified in the survey

5 UK Competency Mapping

This section maps the UK research landscape and identifies the key university and non-university organisations that have competencies in fields relevant to the research themes and capability categories. The section is divided into three parts. The first uses a bibliometric style analysis to provide an overview of the research landscape. The second part interrogates this data further to draw out the key university groups working in fields relevant to the Capability Categories and hence maps the UK research competencies. The final part captures non-university organisations such as technology providers, industry institutions and government organisations, and non-university research organisations that are active in the research themes.

5.1 Research Landscape Overview

The literature identified through the searches described in Section 2.2 has been segmented in a variety of ways to show where the UK academic community is most active, and how this compares to the global community.

The literature has been segmented by searching the titles, abstracts and author key-words for terms related to each research theme. The terms used to identify publications relating to each of the four digital technology research themes are shown in in the Table 5-1. This table is similar to Table 2-1, but has been augmented with additional terms to aid the segmentation. The terms identified with a # have been used for this segmentation, and not for the original search as they would capture erroneous results from the database but are useful segmentation terms within a set of relevant publications.

Table 5-1: Search terms used to segment publications by research theme

*Notes on Table 5-1: * has been used to ensure different endings to words are not excluded; "" are used to return items containing exact phrases; CMMS, CAFM, BAS, IWWS, EAM are all types of facilities management and operation systems. CMMS – Computerised Maintenance Management System; CAFM – Computer-Aided Facility Management; BAS – Building Automation System; IWWS – Integrated Workspace Management System; EAM – Enterprise Asset Management*

As-is reality Capture	On-going reality capture	Information management and sharing	Data-driven decision making
"reality capture"	"sens*"	BIM	"artificial intelligence"
photogrammetry	IoT	"virtual reality"	"machine learning"

As-is reality Capture	On-going reality capture	Information management and sharing	Data-driven decision making
lidar	rfid	"augmented reality"	"automat*"
"point cloud"	"monitor*"	GIS	"simulat*"
"object recognition"	"internet of things"	EAM	"optimi *" #
radar		CMMS	"decision*making" #
"laser scan"		CAFM	"decision support" #
"satellite imag*"		BAS	
drone		IWWS	

The terms used to identify whether the publication relates to either environmental sustainability or existing buildings are listed below:

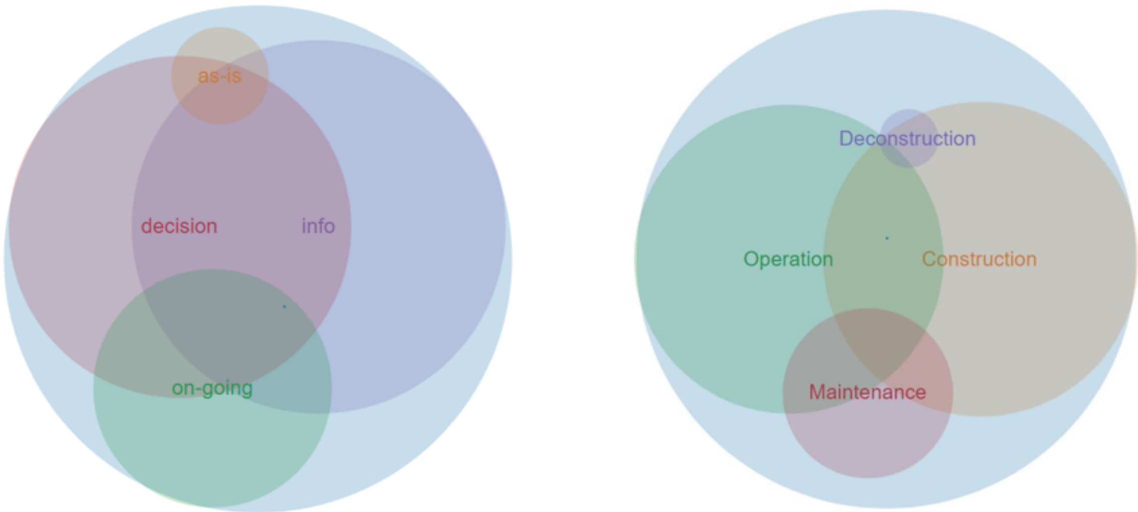
- Environmental sustainability: (i.e. includes search terms: *sustainab**; ecological; energy; carbon; LCA; post occupan**; resource efficien**)
- Existing Buildings: (i.e. includes search terms: *existing; historic; legacy*)

The terms used to identify publications relating to each life-cycle stage are listed here:

- Construction: *construction; retrofit; refurbish*; renovat**
- Maintenance: *maint**
- Operation: *operat*; facilities management*
- Deconstruction: *deconstruct*; demoli**

The * symbol allows for variations on the words. It has not been possible to segment the design life-cycle stage as the search terms do not yield reliable results. The terms used to define the 'Construction' group include terms that would be relevant to the design phase and so one possible reading of the data would be that the 'Construction' group of publications includes publications relating to design. Due to the multiple meanings of the words "*planning*" and "*design*" is has not been possible to segment the data into these life-cycle phases using a bibliometric analysis

Approximately 300 publications identified by our search logic detailed in Section 2.2 were found to have authors affiliated with UK Universities. Figure 5-1: Distribution of research focus across the UK research landscape in digital technologies for buildings, below, describes the distribution of focus in the UK within the broad topic of *digital technologies for the through-life management of buildings*. It covers all life stages and all areas of interest, including, but not limited to, existing buildings and environmental sustainability. The largest background circle area in each Venn diagram below represents the approximately 300 UK publications.



(a) Distribution of different digital technology themes in the UK academic landscape

(b) Distribution of different life-cycle stages in the UK academic landscape

Figure 5-1: Distribution of research focus across the UK research landscape in digital technologies for buildings

Figure 5-1: Distribution of research focus across the UK research landscape in digital technologies for buildings(a) highlights the relatively large current focus in the UK on information management and sharing and data-driven decision making. There is also a strong overlap between information management and sharing, and data-driven decision making i.e. publications frequently look at both aspects of a problem.

Figure 5-1(b) shows the very limited focus on the later life-cycle stage: deconstruction and demolition. This finding is reflected in some of the commentary within the publications themselves. In addition, it is possible to see that no publications have been found that cover all the life-cycle stages i.e. the segmentation suggests that none are truly 'through-life'. It is worthwhile noting that as some design related publications are likely to be included in the 'Construction' group, as discussed above, construction may not be as dominating as the diagram indicates.

Table 5-2, below, provides data on how the UK landscape compares to the global landscape. It is possible to see that the UK under-indexes compared to global figures in As-is reality capture.

In the interim report, Data-driven decision making was combined with Information management and sharing, and the UK was found to over-index compared to the global community in this combined field. However, by separating out these two research themes we have identified that the UK slightly over-indexes compared to the global research community in the use of digital technologies and data to make decisions, but slightly under-indexes compared to the global community in the management and sharing of information.

There is also slightly more focus in the UK on both environmental sustainability and existing buildings, however, broadly speaking the UK landscape does not diverge significantly from the global.

Table 5-2: Comparison between UK research focus and Global research focus

	Global Landscape	UK Landscape
As-is Reality Capture	12%	8%
On-going Reality Capture	29%	29%
Information Management and sharing	74%	68%
Data-driven decision making	51%	56%
Existing Buildings	21%	25%
Environmental Sustainability	43%	51%
Maintenance Issues	15%	14%
Operation Issues	53%	45%
Deconstruction Issues	1%	1%
Construction Issues	45%	50%

Table 5-3 shows the distribution of articles across journals. *Automation in Construction* and *Energy and Buildings* have the largest number of citations for the articles identified by our search. They also have the largest number of articles and amongst the highest citation counts for each article.

Table 5-3: Key journals for UK affiliated articles (data from last five years)

Journal Title	Publisher	No citations	No Articles	Ave. citation per article
Automation in Construction	Elsevier Ltd	353	16	22.1
Energy and Buildings	Elsevier Ltd	247	24	10.3
Building and Environment	Elsevier Ltd	145	12	12.1
Renewable and Sustainable Energy Reviews	Elsevier Ltd	78	5	15.6
Sustainable Cities and Society	Elsevier Ltd	48	5	9.6
Journal of Information Technology in Construction	International Council for Research and Innovation in Building and Construction (CIB)	47	5	9.4
Applied Energy	Elsevier Ltd	29	7	4.1
Journal of Building Engineering	Elsevier Ltd	29	5	5.8
Building Research and Information	Taylor and Francis	23	5	4.6
Building Services Engineering Research and Technology	Sage Publications Ltd	20	6	3.3

Finally, we have looked at the number of publications that are case studies. Case studies are regularly used by academe to disseminate research in a manner that is directly usable by industry. Figure 5-2 shows how the number of case studies published by UK authors within the broad topic of digital technologies for the through-life management of buildings has varied over the last five years. The total number published over the last five years is approximately 50, with a weak increase over time. The drop in 2018 may be due to the 2018 publications still being added to the online database.

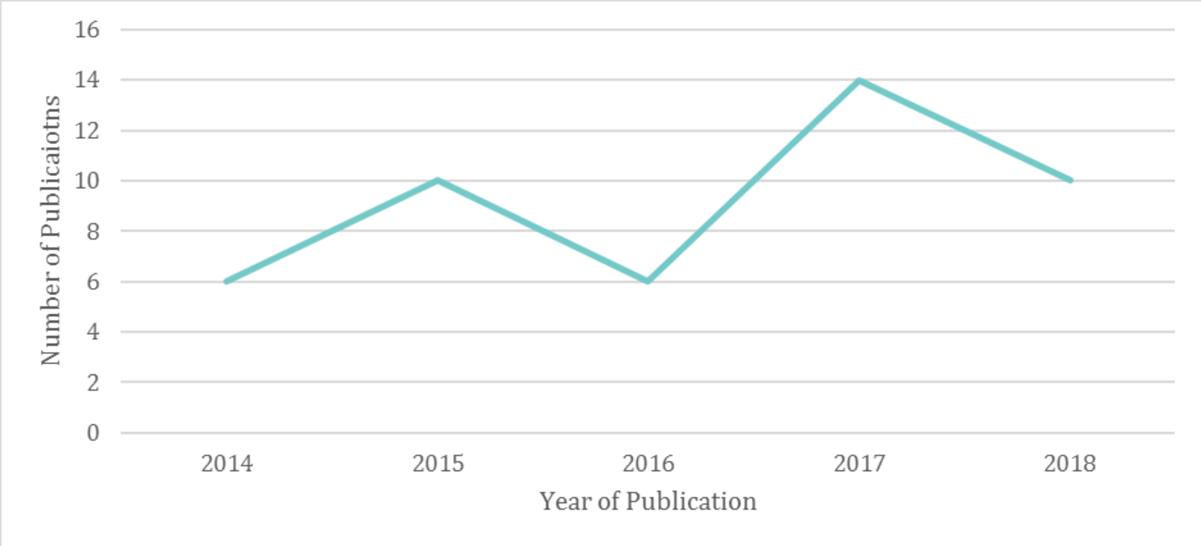


Figure 5-2: Number of case studies published by UK authors over the last five years

5.2 Active University Organisations

Through further interrogation of the publication data set used in the bibliometric style analysis described above, it is possible to draw out which universities are active in the fields related to the Capability Categories by drawing out universities that the authors were affiliated to.

In order to increase the likelihood that only groups that are still active in the field are captured by the search, we have limited the search to the last five years (from 2014 to 2018 inclusive). Table 5-4 provides a high-level summary of the research focus of the most active universities by segmenting their publications according to research theme.

The analysis has been done by searching the title, abstract and author key-words fields for terms grouped by our core 'Research Themes' (as-is reality capture; on-going reality capture; information management and sharing; data-driven decision making). The abstracts of the publications were then reviewed manually to verify the categorisation. A similar analysis has been performed to find whether the publications are undertaken through either the lens of environmental sustainability or existing buildings.

Table 5-4: Research focus of most active universities (number of publications in last five years, with notably higher publication numbers highlighted)

	UCL	Cardiff University	Loughborough University	University of Cambridge	University of Sheffield	University of Nottingham	University of Bath	University of Northumbria	Birmingham City University	Nottingham Trent University	Imperial College London
As-is reality capture	4	1	0	3	2	0	0	0	1	0	0
On-going reality capture	6	4	3	5	4	3	2	1	1	3	2
Information Management and Sharing	14	15	10	7	4	6	3	9	9	2	2
Data-driven decision making	9	11	11	6	8	7	4	5	3	3	1
Existing Buildings	4	5	2	4	5	2	1	2	2	0	1
Sustainability	10	8	10	3	9	9	6	6	2	3	3

Competences in data-driven decision making are well distributed amongst the most active UK universities. Research competencies in As-is reality capture are far less common in the UK and sit within only a few universities giving the competency little resilience. In addition, On-going reality capture is not a highly active research area amongst the most active universities, a finding paralleled in the bibliometric analysis above.

In order to provide more depth to this analysis of the current UK research landscape, the publications have been reviewed for relevance to the Capability Categories. The tables below (Tables 5-5 to 5-17) list the UK universities that have published work that is relevant to each Capability Category and hence indicate a UK research competency in this more specific field.

In the left-hand column, the tables indicate which UK universities the authors were members of at the time of publication. It therefore also gives an indication of collaborative relationships. The second column expands this information by providing the research group within the university, if this data is available. The right-hand column of the table summarises the content of the publication that makes it relevant to the Capability Category. This may not be the primary focus of the publication. The reference to the publication is also included in this last column.

Many publications were undertaken in collaboration with non-UK university organisation and this is captured using * to indicate collaboration with a non-university organisation, and ** to indicate collaboration with an international organisation.

To avoid repetition, a discussion of the key findings from this exercise is include in Section 6 where all the findings from the project are drawn together to form recommendations.

*Table 5-5: **As-is Reality Capture:** Processing of point cloud data (A1)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of Cambridge	Construction Information Technology Lab, Laing O'Rourke Center, Division D, Dept. of Engineering; Centre for Smart Infrastructure and Construction, Dept. of Engineering	Automation of the processing of point cloud data to create objects (Anagnostopoulos *et al.*, 2016)
University of Cambridge	Department of Engineering	Investigation of the issues associated with modelling existing buildings to inform future research (Agapaki, Miatt and Brilakis, 2018)
Birmingham City University	Faculty of Computing, Engineering and the Built Environment	Review of laser scanning technologies (Pärn and D. Edwards, 2017)
The University of Sheffield	Energy 2050, Department of Mechanical Engineering; Advanced Manufacturing Research Centre with Boeing, The University of Sheffield *	Processing of point cloud data to create as-built geometry to use in building energy modelling (Garwood, Hughes, O'Connor, *et al.*, 2018)

*Table 5-6: **As-is Reality Capture:** Surveying hidden services (A2)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of West London	School of Computing and Engineering **	Ground penetrating Radar for locating below ground utilities (Bianchini Ciampoli et al., 2016)

Table 5-7: ***On-going Reality Capture:*** *Occupancy data capture (O1)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of Nottingham	-	Review of occupancy monitoring technologies (Naghiyev, Gillott and Wilson, 2014)
University of Cambridge	-	Using wearable sensing technologies to measure the effect of spaces on social interactions (Brown *et al.*, 2014)
University College London	Energy Institute	Approach to capture occupant behaviour responses (Gauthier and Shipworth, 2015)

Table 5-8: ***On-going Reality Capture:*** *Building performance data capture (O2)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of Bath	Department of Architecture and Civil Engineering	An approach to reduce the costs associated with research that uses sensors (Lovett *et al.*, 2016)
Imperial College London	*	Close performance gap using wireless sensor networks (Noye, North and Fisk, 2016)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of Bath	Department of Architecture and Civil Engineering; Department of Psychology; Department of Computer Science	Using IoT to assess thermal properties of the building (Ramallo-González *et al.*, 2018)
University College London	Computer Science **	Internet Protocols for IoT (Varakliotis *et al.*, 2014)
Nottingham Trent University	School of Science and Technology **	Low cost open source domestic electric energy consumption monitoring (Peytchev *et al.*, 2016)

*Table 5-9: **Information management and sharing:** Data storage and data exchange (IM1)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University College London	*	Collating condition information for condition reporting using parametric approaches (Pocobelli *et al.*, 2018)
University College London	-	An approach manage and exchange IoT and security data (Kirstein and Ruiz-Zafra, 2018)
Northumbria University	Faculty of Engineering and Environment **	Investigates making use of an object oriented semantically rich model for compliance checking (Malsane *et al.*, 2015)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Loughborough University	School of Civil and Building Engineering * **	Extension to IFC schema for building performance simulation information (Cemesova, Hopfe and McLeod, 2015)
Loughborough University	School of Civil and Building Engineering *	IFC compliant renewable energy simulation tools (Gupta *et al.*, 2014)
Cardiff University	School of Computer Science and Informatics; School of Computer Science and Informatics	Automated federation of BIM information (Beach *et al.*, 2017)
Northumbria University	Faculty of Engineering and Environment	Using BIM for environmental assessments and certifications (Alwan, Greenwood and Gledson, 2015)
University College London Imperial College Business School	Comp. Sci. Dept. Univ. College London, Digital City Exchange Imperial College Business School *	Software architecture for Smart building including addressing interoperability issues (Suzuki *et al.*, 2014)

*Table 5-10: **Information management and sharing:** Transfer of information from construction stage to operation stage i.e. handover (IM2)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Cardiff University	School of Engineering, BRE Centre for Sustainable Construction	Review of using 2D information to generate 3D as-built models (Gimenez *et al.*, 2015)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of Teesside Northumbria University	- * *	Decision support system to aid the incorporation FM values at the start of a project (Rodriguez-Trejo *et al.*, 2017)
Birmingham City University	Faculty of Technology Environment and Engineering	An approach to extent the use of COBie to address cost to the FM team of updating and maintaining as-built BIM (Pärn and D. J. Edwards, 2017)
Northumbria University	Faculty of Engineering and Environment *	Process model to gather the required FM information for incorporation in to the BIM (Florez and Afsari, 2018)
The University of Nottingham	Department of Civil Engineering * *	Virtual reality to support construction to FM handover (Neges *et al.*, 2017)
Teesside University	Technology Futures Institute	The development of asset information models that meet owners' data needs (Patacas *et al.*, 2016)
University College London Birmingham City University	The Bartlett School of Construction and Project Management, University College London, London; Faculty of Computing, Engineering and the Built Environment (CEBE), Birmingham City University; School of Engineering and the Built Environment, Birmingham City University * *	Development of construction FM handover requirements (Hosseini *et al.*, 2018)

Table 5-11: ***Information management and sharing:*** *Capturing and communicating uncertainty (IM3)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Edinburgh Napier University University of Cambridge	Institute for Sustainable Construction, Edinburgh Napier University; Department of Engineering, University of Cambridge	Managing uncertainty in LCAs (Pomponi, D'Amico and Moncaster, 2017)
Cardiff University Plymouth University	Engineering School, Cardiff University; Environmental Building Group, Plymouth University	Using parametric modelling to address complexity and uncertainly in modelling the impact of future climate change (Li, De Wilde and Rafiq, 2014)
University of Bath	Department of Architecture and Civil Engineering * *	Investigation of sources of uncertainty in building assessment tools (Jain *et al.*, 2015)

Table 5-12: ***Information management and sharing:*** *Sharing asset data across the industry (IM4)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University College London	Dept. of Civil, Environmental and Geomatic Engineering	Published point cloud datasets for use as benchmarks for the research community (Thomson and Boehm, 2014)

Table 5-13: ***Information management and sharing:*** *Management of building stock data (IM5)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University College London	Dept. of Geomatic Engineering * *	An approach to integrate 3D BIM with 3D GIS data (Baik, Yaagoubi and Boehm, 2015)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University College London	UCL Energy Institute, Bartlett Faculty of the Built Environment	Development of 3D model of British building stock '3D Stock' (Evans, Liddiard and Steadman, 2017)
University College London, London	Institute for Environmental Design and Engineering, The Bartlett School of Environment, Energy and Resources **	Integration of BIM, GIS and energy simulation data by developing District Data Model (DDM) (Costa *et al.*, 2016)
Nottingham Trent University	School of Architecture, Design, Built environment	Review of 2D and 3D GIS data for energy forecasting (Chalal *et al.*, 2016)
University of Cambridge	Department of Architecture	Integration of data for interdisciplinary city design (Jin, Jiao and Jahashahi, 2018)

Table 5-14: ***Information management and sharing:*** *Keeping and up to date model and creating a single source of truth (IM6)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Cardiff University	-	BIM as a 'comprehensive information provider' an incorporating Virtual Reality technologies (Wang *et al.*, 2014)
Cardiff University	School of Computer Science & Informatics	Development of a 'Hub' to support integration between sensors (Anthi *et al.*, 2018)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University College London	Centre for Advanced Spatial Analysis	Case study of the use of a digital twin (Dawkins *et al.* 2018)
University of Cambridge	Institute for Manufacture, Department of Engineering	Creation of a Digital Twin for facilities management and occupant wellbeing https://www.ifm.eng.cam.ac.uk/news/digital-twins/ (no known publications as yet)

It should be noted that there is a body of literature being produced within the UK that considers Digital Twins for infrastructure, but this sits outside the scope of this report and so has not been detailed.

Table 5-15: ***Data-driven decision making:*** *Optimisation during design (D1)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Loughborough University Nottingham Trent University	Department of Civil and Building Engineering, Loughborough University; School of Architecture, Nottingham Trent University	Energy demand forecasting (Menezes *et al.*, 2014)
The University of Sheffield	Energy 2050, Department of Mechanical Engineering; Advanced Manufacturing Research Centre with Boeing *	Combining BEM (Building Energy Modelling) and MPS (Manufacturing Process Simulation) for holistic design of factories (Garwood, Hughes, Oates, *et al.*, 2018)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of Reading University College London	University of Reading: Technologies for Sustainable Built Environments; School of Psychology and Clinical Language Sciences; School of Construction Management and Engineering; The Bartlett School of Environment, Energy and Resources, University College London *	Research into occupant behaviour to inform modelling energy performance (Tetlow *et al.*, 2015)
University of Exeter University of Bath	College of Engineering, Mathematics and Physical Sciences, University of Exeter; Department of Architecture and Civil Engineering, University of Bath	Optimisation and evaluation algorithm to address current longevity of required computation time (Ramallo-González and Coley, 2014)
University of Cambridge	Department of Engineering * *	Optimised generation of re-fabrication sequences for robotic prefabrication systems (Kasperzyk, Kim and Brilakis, 2017)
Loughborough University University of Stirling	School of Civil and Building Engineering, Loughborough University; Computing Science and Mathematics, School of Natural Sciences, University of Stirling	Optimisation of the refurbishment of domestic building stock (He *et al.*, 2015)
Nottingham Trent University	Design and the Built Environment, School of Architecture	Optimisation of services layout using parametric tools (Medjdoub and Chenini, 2015)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
University of Strathclyde Northumbria University University of Strathclyde	Faculty of Engineering, University of Strathclyde; Faculty of Engineering & Environment, Northumbria University; Faculty of Computer and Information Sciences, University of Strathclyde	Review of machine learning for forecasting and improving building energy performance (Seyedzadeh *et al.*, 2018)
University College London Coventry University	UCL Institute for Environmental Design and Engineering, University College London *	Using BIM and LCAs to develop efficient structural systems (Eleftheriadis, Mumovic and Greening, 2017)
Oxford Brookes University Birmingham City University	School of Built Environment, Oxford Brookes University; School of Engineering and the Built Environment, Birmingham City University	An approach to using energy consumption data and BIM systems to create a 'feedback loop' for design and FM improvements (Oti *et al.*, 2016)

Table 5-16: ***Data-driven decision making:*** *Holistic optimisation during operation (D2)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Imperial College London	Data Science Institute	The use of data science for energy management (Molina-Solana *et al.*, 2017)
University of Nottingham	Department of Architecture and Built Environment	Automated control of shading devices (Eltaweel and Su, 2017)

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Cardiff University	Institute in Sustainable Engineering, School of Engineering * *	BIM to support energy efficiency in operations phase (Petri *et al.*, 2017)
University of Sheffield	Electronic and Electrical Engineering ; Civil and Structural Engineering	Review of the automated creation of predictive models for use with building system control technologies (Rockett and Hathway, 2017)
Nottingham Trent University	Computing and Technology Dept	Prototype for smart house system addressing cost and usability (Howedi and Jwaid, 2017)
Loughborough University	Center for Biological Engineering	BIM based decision support tool for maintenance, retrofit an operation (Fouchal, Hassan and Firth, 2014)
University of Nottingham	Department of Architecture and Built Environment, Faculty of Engineering *	Review of current building control systems (Naylor, Gillott and Lau, 2018)
Coventry University	School of Computing, Electronics and Maths School of Energy, Construction and Environment	Display of real-time energy consumption (Liu *et al.*, 2018)

*Table 5-17: **Data-driven decision making:** Managing waste and extracting end of life value (D3)*

UK University of Authors	Departments of Authors at UK Universities	Relevant topic included in the publication
Loughborough University	School of Civil, Building Engineering	Using BIM for construction waste minimisation (Liu *et al.*, 2015)
Northumbria University	Faculty of Engineering and Environment, Department of Architecture & Built Environment	BIM based collaboration to address waste (Alwan, Jones and Holgate, 2017)
University College London	Dept of Civil, Environ & Geomatic Eng, Faculty of Engineering Science; Centre for Urban Sustainability and Resilience	Databases to capture reusable materials in buildings (Rose and Stegemann, 2018)
University of Sheffield University of Cambridge	Department of Civil and Structural Engineering, University of Sheffield; Department of Engineering, University of Cambridge	Recommendation to use databases to support re-use of structural steel (Densley Tingley, Cooper and Cullen, 2017)

5.3 Active Non-university Organisations

Through the literature study and other investigations for the project, the team have identified a number of organisations which, in the majority, represent the range of users, developers and producers of the digital technologies in question.

A major contribution to this work was from attending the Digital Construction Week Conference (London, Oct 17th/18th 2018). This conference was a clear indication of the desire for digitisation in the industry and many key organisations and companies were represented. Although the focus of the conference was construction, there was also representation from the planning and design, maintenance and, operation and evaluation life-stages. From reviewing the conference programme, the most well represented technology type, using our framework of the three research themes, was information management and sharing.

Table 5-18 shows the organisations determined, to date, to be key organisations in digital technologies for through-life management of buildings, which are active in the UK.

Table 5-18: Non-academic organisations active in the UK in relevant areas

Name	Organisation Type	Outputs	Information Management and Sharing	As-is Reality Capture	On-going Reality Capture	Data-driven Decision Making
BEIS: Department of Business, Energy and Industrial Strategy	Government Department	policy recommendations				
MHCLG: Ministry of Housing, Communities and Local Government	Government Department	policy and standards (Building Regulations)				
BSI British Standards Institution	Industry Guidance	standards recommendations; industry guidance and training				
NBS National Building Standards	Industry Guidance	standards recommendations; industry guidance and training				
UK BIM Alliance	Industry Guidance	Industry guidance and training				
Arup	Practitioner	design tools; pilot projects				
Hoare Lee	Practitioner	pilot projects; technology development				
Laing O'Rourke	Practitioner	SmartSet project with Advanced Manufacturing Research Centre				
McGee	Practitioner	digital technologies (especially mobile apps)				
Ramboll	Practitioner	design tools; pilot projects				

Name	Organisation Type	Outputs	Information Management and Sharing	As-is Reality Capture	On-going Reality Capture	Data-driven Decision Making
Thornton Tomasetti	Practitioner	design tools; analysis tools				
BIFM: British Institute of Facilities Management	Professional Body	standards recommendations; industry guidance and training				
CIBSE: Chartered Institute of Building Services Engineers	Professional Body	industry guidance and training				
ICE Institution of Civil Engineers	Professional Body	industry guidance and training; standards recommendations;				
RIBA Royal Institute of British Architects	Professional Body	surveys of current industry state; guidance on good practice				
Royal Institute of Chartered Surveyors	Professional Body	industry guidance and training				
GVA	Property Developer	pilot projects; technology development				
BAMB: Buildings As Material Banks	Research	design tools; policy and standards recommendations; business models; pilots;				
BRE Building Research Establishment	Research	tools and research partnerships				
Cambridge Architectural Research	Research	tools and research				
Centre for Sustainable Energy	Research	tools and research				
Digital Catapult	Research	Digital technologies, research, guidance				

Name	Organisation Type	Outputs	Information Management and Sharing	As-is Reality Capture	On-going Reality Capture	Data-driven Decision Making
Future Cities Catapult	Research	Digital technologies, research, guidance				
The Alan Turing Institute	Research	research				
Autodesk	Technology Provider	design tools				
Bechtel	Technology Provider	digital equipment				
Leica Geosystems	Technology Provider	Digital equipment; pilot projects				
Trimble	Technology Provider	Digital Equipment				
Faro Technologies UK Ltd	Technology Provider	Digital technologies, technology development				
HeatSave	Technology Provider	Digital technologies (BMS)				
Energy Systems Catapult	Technology Support Agency	digital technologies (especially electricity demand and supply)				

6 Recommendations

This section draws together the key capabilities, risks and barriers identified through the literature review, the interviews and the expert panel discussions. Through a comparison of these three datasets we have grouped the capabilities into the thirteen Capability Categories discussed below and included examples of the specific capabilities required, as well as the associated risks and barriers. Further detail and the raw data sets are provided in the relevant sections of this report.

In each of the sections below, the required capabilities are reviewed against the current UK competences and any gaps in the competency landscape have been highlighted.

As-is Reality Capture: Processing of point cloud data (A1)

All three data sources indicated that there is a requirement to develop capabilities in the UK around the specification and processing of point cloud data suggesting that that evidence base for this need is strong. The capability related to this capability category was identified as high impact by the expert panellists, but then ranked second priority out of the two capability categories that fall into as-is reality capture.

Both the literature review and expert panel draw out the need to automate the process of converting the point cloud data into a useable object model. Although the interviews did not suggest automation of this process, they did suggest that it should be possible to process the data overnight. The interviews and the literature review also highlighted the need for capabilities around facilitating the inclusion of semantic data into the models that are generated using laser scanning. The literature review's recommendations in this area focused on object and material recognition, although the interviews reinforced this, they also suggest augmenting the data with asset tagging.

All three data sources highlighted the need to address the increasingly large models and data sets that are currently unwieldy. However, they approached the problem in two different ways: the literature review suggested technical solutions such as cloud servers; whereas the expert panel suggested that the project team should specify more carefully what survey data should be collected in the first place.

The expert panel alone identified a requirement for contractual solutions to allow the model to be 'trusted'. They commented that without contractual commitments around reliability, the survey models generated have limited value. This is currently a barrier to extracting the full value from both existing and future technologies.

The expert panel suggested that alongside research, technology providers are necessary to fill the gaps in the current technology solutions. In addition, institutions are needed to develop the contractual basis for understanding the reliability of the model and allocating risk to suitable parties. The review of the UK research competences indicates that there are several universities working in this field and so the UK research competence is relatively resilient. The review of the non-university organisations active in the UK suggest that there are technology providers working in this field.

As-is Reality Capture: Surveying hidden services (A2)

The need to be able to unobtrusively capture data about hidden building elements and services did not feature strongly in the literature reviewed but was drawn out of both the interviews and expert panel session. The capabilities related to this capability category were given a high prioritisation scores of 45 out 60, and ranked first within the theme of as-is reality capture.

The interviews and expert panel suggested that there is a need to develop suitable technology. However, the panel also indicated that there was a need for cost-benefit analyses to support the business-case for using the technology that is available and hence remove a barrier to its use. Finally, the expert panel repeated the requirement from the capability above, indicating that there is again a need to have contracts that provide a legal commitment around accuracy and can be used to manage the risks of inaccuracy.

The review of the UK university organisations indicates that there are very few UK based researchers working directly in this field. It should be noted that there are inevitable limitations to the literature methodology and therefore the search is not exhaustive. However, given that the numbers found were low, it does indicate a low UK research competence with low resilience. The review of the non-university organisations active in the UK suggest that there are technology providers working in this field.

On-going Reality Capture: Occupancy data capture (O1)

The literature review, interviews and expert panel discussion all recommended that the industry needs to be able to capture more data about occupants to optimise buildings and building systems for the occupants' true behaviour and experiences. The expert panel and the literature indicated that key risks are around data privacy and security. Without management of this risk, they become barriers. The expert panel suggested that the current 'cultural silos' of design and operation result in a barrier to this data collection, whereas the literature review suggested that there are still technical issues around the sensing and monitoring technology itself.

The UK competence review suggests that there are a few universities, but not many active, in this field, and a range of technology providers. In addition, there are a selection of government bodies and institutions that have interests in this broad area, but it is not clear how active they are in this specific field. The expert panellists suggested that clients needed to take a leading role in addressing this, but they could not think of a suitable client body that would support clients in doing this.

On-going Reality Capture: Building performance data capture (O2)

All three data sources highlighted the need to capture more data about the building itself, specifically any changes over time. The expert panellists gave capabilities relevant this Capability Category priority rankings 1st, 2nd, 3rd and 4th out of the 6 capabilities within the theme of on-going reality capture.

Both the literature review and the interviews noted that there are unresolved issues about linking sensor and monitoring equipment with Facilities Management (FM) systems. In addition, the interviews suggested that challenges associated with installing new sensor systems could be overcome by using existing systems to collect related data and then interpreting results e.g. using CCTV with image recognition. The expert panel discussions drew out the need to capture the large range of small changes such as installation of a new door seal, and suggested approaches such a digital log-books and material passports.

The expert panel indicated that there is a current barrier around cost which could be overcome if there was a greater availability of cost-benefit analyses or supporting data. In addition, they suggested that case-studies would be valuable. The expert panellists suggested that these areas required a large amount of research input and there are several university organisations active in this area.

Information management and sharing: Data storage and data exchange (IM1)

All three data sources raised the need for improved data storage and exchange. The two capabilities relating to this topic were highlighted by the expert panel as high impact and prioritised as 4th and 9th out of 11 in the expert panel prioritisation exercise.

They all highlighted that it is currently not possible to digitally store all the information that you may need, for example: data about building crafts relevant to existing buildings; data about end of life-cycle stages; some materials data; and data about decay. This was a current barrier to using digital technologies for related activities.

In addition, they all discussed the need to improve the accurate exchange of the data between software: literature review revealed a current lack of capabilities in this area surrounding BIM to LCAs, the interviews also raised current issues about exchanging data between BIM and other forms of analysis.

The expert panel indicated that this is an area where further research is required, and the UK university organisation review indicates that there are a large number of UK universities working in this field. The expert panel also highlighted the need for industry initiatives and standards bodies to play a strong role in this development work, and the non-university organisation review suggests that there are active organisations in the UK with competencies in this area.

Information management and sharing: Transfer of information from construction stage to operation stage i.e. handover (IM2)

Both the interviews and the literature review revealed that there is a strong need to improve capabilities around the transfer of information from the construction life-cycle stage to the operation life-cycle stage. The Technology Map, in Section 0 also showed that technology for operation and maintenance are thought of by industry as 'low efficacy'.

The expert panel considered this high impact but it was only ranked 8th out of 11 capabilities within the theme of information management and sharing. However, given the parallels in the discussions around this topic from all three data sources there is a strong evidence base to indicate that this is a required capability.

The interviews and expert panel agreed that there is currently a lack of understanding of what information should be transferred. The literature review, interviews, and expert panel all suggested that the data exchange standards between the models used for managing construction information, and those used for managing FM systems are currently insufficient. The expert panel listed standards developers as key actors in resolving this issue alongside researchers. The review of the UK universities shows that there are a number of universities with current relevant competences.

Information management and sharing: Capturing and communicating uncertainty (IM3)

The literature review, interviews and expert panel all highlighted the need to be able to capture and communicate uncertainty and therefore this has been drawn out as a key Capability Category. Although all three sources brought this issue to light it does not have such a strong evidence base as the other Capability Categories. Relatively little literature highlighted it, only a few interviewees addressed it, and, although it was raised at the expert panel session it was ranked as low impact (and high research input). The review of UK university organisations indicates competences in the UK are present, but among relatively few universities.

Information management and sharing: Sharing asset data across the industry (IM4)

A very strong theme from the expert panel session was the need to develop an industry capability to share data sets about assets to allow the industry to learn and improve. The expert panel identified several capabilities that fall into this capability category and they were given very high priority rankings (including 1st, 3rd and 5th out of the 11 that fall into the theme of information management and sharing). The interviewees also raised this issue, but more in relation to sharing lessons learnt, rather than sharing the data itself.

The expert panellists suggested that a key barrier was the reluctance of organisations to share data, as well as the lack of a centralised database to store shared data. They identified risks around privacy and security. The existing global academic literature has identified that there is a need to share this data, but little literature explored how this could be done. In the UK, very few universities were identified as active in this research area. This is likely a key competence gap that would need to be addressed for the capability to be developed.

Information management and sharing: Management of building stock data (IM5)

All three data sources drew out the theme of managing building stock data. Both the interviews and the literature review revealed a need to be able to draw together existing building data to become building stock data. However, while the literature approached this from the perspective of an urban scale data store, the interviewees were more focused on issues related to large asset portfolios or managing large estates.

Although the expert panellists did not identify this as a high impact capability (and so it was not taken forward to the plenary to allow further details to be elicited), four of the capabilities put forward by individuals in the group discussions were related to this topic.

Within the UK there are several universities active in this area who are focusing on the integration of individual building data into larger data sets.

Information management and sharing: Keeping an up to date model and creating a single source of truth (IM6)

The literature, interviews and expert panel all indicate that there is a need to be able to maintain a model that will provide a single source of up to date information. This requirement aligns with ideas around digital twins. The literature suggests that there is a need to facilitate the updating of the information in the model, possibly through automation. The interviews suggested that development in this area needs to focus on making it easier for operatives (during both construction and operation) to update the model in real-time. The expert panellists gave this issue a priority ranking of 2nd out of 11 and suggest that current barriers include contractual requirements and lack of proof of value. The UK competences review indicates that relatively few UK universities are active in this field.

Data-driven decision making: Optimisation during design (D1)

Both the literature review and interviews emphasised the need to use digital technologies and data to improve and optimise decision making during the design process. However, whereas the literature focused on being able to optimise with multiple complex design criteria, the interviewees focused more on removing repetitious tasks and automating design using tools such as parametric modelling.

The expert panel did highlight this issue with a related capability to be able to incorporate unquantifiable information into decision making. They ranked this issue 1st out of the three capabilities that fall into this theme of data driven design, but it should be noted, that all three were given very similar prioritisation scores and so the ranking does not suggest a clear top priority. The panellists also raised this issue in the small group sessions where they discussed parametric modelling simulation to improve decision making.

This is a highly active research area in the UK, with a range of universities currently producing publications that indicate relevant competences. The expert panel indicated that, alongside researchers, practitioners would need to be involved in developing capabilities in this area. Our review of non-university organisations revealed that there are several practitioner organisations that are developing tools in this field.

Data-driven decision making: Holistic optimisation during operation (D2)

The literature review, interviews and expert panel all highlighted the need to be able to refine and optimise the building's performance during operation and base this optimisation on a range of data sets that cover a range of different criteria.

The literature focused on automating decision making around energy management and systems operation, whereas the interviews and expert panel focused more on developing an understanding of what industry should be looking to optimise in the first place. For example, understanding whether occupant productivity should be incorporated in the criteria (from the expert panel), and which other aspects of human behaviour it is really necessary to optimise for (interviews).

The Technology Map produced through the interview data suggests that there are few effective digital technologies for the operation and evaluation life-cycle stages, possibly indicating a gap and hence an opportunity for further capabilities. In the UK there are many university organisations active in this field, indicating a robust competency.

Data-driven decision making: Managing waste and extracting end of life value (D3)

The interview data highlighted with multiple examples that industry requires capabilities in this area. In addition, the Technology Map showed that there are currently relatively few digital technologies for end life cycles stages, with the ones that do exist having low efficacy. Although, the review of the global literature drew out little related to required capabilities, the literature and bibliometric analysis did highlight that this is a field with very limited research attention. For these reasons, this capability category has been included as a recommendation. The interviews suggested that there are needs around waste sorting, as well as methods to record, recognise and extract value from materials for re-use. Our review of UK competences suggests that there are both university and non-university organisations active in this field, but relatively few.

Risks

Although key risks are included under the discussions of the Capability Categories above, there are some common themes. The literature review, interviews and expert panel discussion all highlighted risks around data privacy and data security. In particular, this was in relation to capturing occupancy data, as well as sharing asset data across the industry.

The literature review suggests that there is a concern about the rate of change of technology, and the risk of installing technologies that quickly become redundant or that data will become inaccessible in the future. The expert panel highlighted the need for compatibility of data exchange standards and suggested that technology providers and standards developers need to be involved in addressing this.

Barriers

Barriers central to the discussions of the Capability Categories have been included under the headings above. However, there are five barriers that are re-occurring: trusting the data; cost of technology; ownership of data; lack of required skills and industry structure.

- Both the interviews and the expert panel discussion revealed issues in the industry around trusting data from others or trusting the models they produce. The inability to rely on a model without taking on risk is a key barrier to their wider use and to their efficient use or integration into design, construction and operation processes. Solutions included contractual methods to allocate risk, placing a contractual requirement on the model producer to verify information, as well as requirements to communicate uncertainty.
- Cost of technology was raised; however, it was predominantly in the context of a requirement to understand the true cost and benefits to allow for a business case for investment to be made. The interviews did suggest that the cost of technologies prevents smaller organisations from taking them up. Given the large number of small organisations in the UK built environment industry, this may be a significant issue.
- The literature, interviews and expert panel all suggested that the ownership of data by organisations without incentives or willingness to share prevents the industry from learning from past issues, or about the true performance of buildings.
- Both the literature review and the interviews strongly indicated that a barrier to the wider uptake of digital technologies for Facilities Management activities was a lack of

required skills. The literature review suggested skills were required at the manager level for the maintenance and operation of the systems, whereas the interviews suggested that skills were required at operator levels. Both suggested a lack of skills combined with a lack of awareness of the benefits resulted in low buy-in from these stakeholders.

- Although not highlighted in the literature, both the interviews and the expert panel suggested that the industry structure is a barrier to the adoption of digital technologies. They included issues such as the need for the use of new digital technologies on a project to be led by clients, but clients who do not frequently commission buildings are not informed enough. In addition, current contracts and procurement methods are not well aligned to the workflows that are best able to exploit digital technologies. This may include issues around risk allocation and sharing data.

Basis for Delivery and Dissemination

The basis for delivery of the required research has been discussed under each of the Capability Category headings above. Most of the Capabilities Categories are aligned with robust research competencies in the UK. However, there are two capabilities that the competency review has indicated little current UK activity and therefore may represent a gap. These are: surveying hidden services and structure unobtrusively to facilitate planning and costing without disrupting the current use of a buildings; and sharing data across the industry to facilitate industry wide improvement.

Other than university organisations, the basis for delivery is quite strong. There are the largest number of active organisations in Information management and Sharing, which reflects well on the larger number of capability categories in this area. There is perhaps a lack of support in the form of Industry Guidance, as only two organisations have been identified in this area outside of the Information management and sharing theme. This chimes with the identified need for standards to be developed in order to facilitate the development of several of the capability categories.

7 Conclusions

This report has set out to define the research landscape in digital tools for the creation and through-life management of the built environment, with specific reference to legacy buildings, and to identify what new or enhanced capabilities the UK will need in the future "to create, exploit and enjoy digital built Britain over the next several decades".

The research programme undertaken to achieve this has had four main components: a literature review, in which some 50 papers were reviewed in detail to draw out required capabilities (Section 2); a review of the UK research landscape in which 300 paper were reviewed to asses UK competency (Section 5); an associated review of the competencies of UK non-university organisations involved in this field (Section 5); a set of semi-structured interviews with 22 specialists, mostly practitioners, which have helped to understand the currently perceived needs of professionals (Section 3); and an expert panel meeting, at which 26 specialist practitioners from built environment professions were brought together for a day's discussion to define the required capabilities, and to prioritise them (Section 4).

Four main research themes were identified through the early literature review identified as: As-is reality capture, On-going reality capture, Information management and sharing and Data-driven decision making. These research themes have been further subdivided into 13 Capability Categories.

The outcome of the literature review, interviews and expert panel have been brought together in a series of recommendations for capabilities within each of the 13 Capability Categories needing further research and/or development (Section 6) along with the associated barriers and risks, and the type of organisation best placed to carry out the necessary work. Existing UK competence for such work has been identified, and gaps noted.

Most of the Capabilities Categories have been found to be aligned with robust research competences in the UK. However, there are two capabilities for which the competency review has indicated little current UK activity and therefore may represent a gap. These are: surveying hidden services and structure unobtrusively to facilitate planning and costing, without disrupting the current use of buildings; and sharing data across the industry to facilitate industry wide improvement.

The recommendations given are subject to some limitations which should be noted. First, it was necessary to limit the scope of the project to a manageable scale, and this required limiting the scope of the literature search accordingly. Infrastructure other than buildings has not been explicitly considered. Buildings, and particularly legacy buildings and their management, have been a focus of the investigation, and sustainability issues have been given a special emphasis, chiefly in the selection of documents to review. Secondly, the selection of required capabilities was strongly influenced by the opinions and experience of the specialists involved. These represented as broad a spectrum of the built environment professionals as was possible but was inevitably not totally representative. In particular, facilities management was poorly represented during both the interviews and the expert panel.

The review of UK competences is also by no means complete. It is largely derived from the literature review and published reports and is added to indicate the most active groups. Many currently active organisations will not have been identified.

Nevertheless, it is believed that this report makes a significant contribution to defining the capabilities which will be needed to develop Digital Built Britain in the coming years, to identifying the research efforts needed to develop them, and to reviewing the competences available for this aim, and identifying significant gaps.

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9 Appendices

A. Interview Sheet for Participants
B. Interview Note Template
C. Expert Panel Participants
D. Full List of Capabilities Produced at Expert Panel Session

Appendix A

Information Sheet for Participants*

Study Title: The digital technology landscape for the through-life management of legacy built assets

Principal Investigator: Robin Spence, Cambridge Architectural Research

We would like to invite you to take part in our research regarding the use of digital technology in the through-life management of legacy built assets.

The overarching aim of the research is to understand the existing state of digital technology in use in industry and currently under research. Through this we intend to identify the developmental needs, both technical and non-technical, to fully support the through-life management of legacy built assets with digital technologies.

How do we want you to participate?

We would like to arrange an interview with you to discuss your experience working with existing buildings and the use of digital-technology in their through-life management. The interview will be semi-structured, meaning that we will produce a set of questions to ask before the interview takes place but depending on what we discuss, there may be additional questions to allow for elaboration of a particular topic of interest.

The interview should take about 30 minutes and will take place on the phone or in person – this will be organised via email and arranged to be at a time which is convenient for you. The core questions for the interview are included overleaf.

Who is funding this study?

The project is funded by the Centre for Digital Built Britain, a collaboration between the University of Cambridge and the UK Government's Department of Business Energy and Industrial Strategy.

Will your participation be confidential?

If you agree to be interviewed, your name will not be included in any research reports or papers and will not be circulated to others, unless permission is received to do so.

Who else is taking part?

We are contacting a range of stakeholders involved in the through-life management of existing buildings including (but not exclusively): academics; architects; building owners; contractors; facilities managers; industry bodies (e.g. BSI or BRE); M&E engineers; quantity surveyors; structural engineers; sustainability consultants and technology providers.

What are the advantages of taking part?

We will keep you up to date with papers and reports that we are publishing, this will allow you to keep track of how the research is progressing. The end goal of the project is to identify gaps in the research and development of digital technologies for the through-life management of legacy built assets and therefore inform further research and development to ensure the UK has a fully digitally supported through-life management process.

What else do you need to know?

Ideally we would like to record the interview using a voice recorder. Notes will be taken during the interview and these will then be coded and analysed. If deemed beneficial, some interviews may be transcribed. Before the interview commences, we will remind you of this and check with you verbally that it is ok. Notes from the interview and any transcripts will not be circulated. If you want to discuss anything 'off the record' during an interview, recording will be stopped. If you would prefer not to be recorded, please inform us before the interview takes place.

What happens now?

Please read through the consent form, on page 3 of this document, and confirm via email that you are happy to be interviewed and we will arrange a date for the interview to take place.

Interview Format

The interview will be semi-structured and based around the following list of questions. If there is something that we think would be good to discuss in more detail, we will also follow this up.

- Could you please tell me how you are involved in the management of existing buildings?
- What digital technologies do you currently use on a regular basis in this role, with regard to existing buildings?
  - Please could you also explain their functions, at which point in the process it is used and their efficacy in more detail?
- What are the main benefits of using these digital technologies in existing buildings?
- What are the main drawbacks of using these digital technologies with existing buildings and how could they be overcome?
- What seem to be the main barriers to uptake of digital technologies for the management of buildings through their lifespan?
- With new technologies becoming available, are there any which you are planning to implement on projects in the near future?
- Are there other areas of your work with existing buildings where new digital technologies could be beneficial?
- What do you consider to be the major risks of implementing more digital technologies in the industry?

Glossary

Through-life management: this refers to the range of activities which occur at any stage of a building project, from conception and planning all the way through operation to deconstruction/demolition.

Legacy built assets: within this project, legacy built assets refers specifically to existing buildings, rather than infrastructure, which were built at a time when digital technologies were not as prevalent, or even non-existent.

Life-stages: We consider the life of a building to consist of "Planning and Design", "Construction", "Maintenance", "Operation and Evaluation" and "Deconstruction"

Participant Consent Form

Study Title: The digital technology landscape for the through-life management of legacy built assets

Principal Investigator: Robin Spence

Address: 25 Gwydir St, Cambridge CB1 2LG

Contact phone number: 01223 460475

1. I confirm I have read and understood the information sheet which explains the research project.
2. I understand that my participation is on a voluntary basis and I am free to withdraw at any time without giving reason and without there being any negative consequences. I am free to decline to answer any questions during the interview.
3. I understand that the interview will be recorded, notes will be taken, and the recording may be transcribed by the researcher. If I am not happy to be recorded, I have informed the researcher of this.
4. I understand that my responses will be kept confidential (unless permission is obtained otherwise).
5. I am happy for the research to be used for papers published relating to the project.
6. I agree to take part in the above research project.

If you are happy with all of the above, please confirm your willingness to participate and acceptance

by emailing Robin Spence (robin.spence@carltd.com).

* Template based on previous information sheet used by research team: Baker, H. (2016) The decision to demolish or adapt existing buildings on masterplan regeneration sites, PhD 1st Year Report, University of Cambridge, Cambridge, UK

Appendix B

CDBB Project Interview Notes

CAR

Date: xxxx

Duration: xxxx

Interviewer: xxxx

Interviewee: xxxx

Experience			
xxxx			
Technology	**Function**	**Life-stage**	**Efficacy**
xxxx	xxxx	xxxx	xxxx
Benefits			
xxxx			
Drawbacks			
xxxx			
New Technologies			
xxxx			
Planning to use		**Need to be developed**	
xxxx		xxxx	
Risks			
xxxx			

Other
xxxx

Appendix C

Expert Panel Participants:

Ron Bakker, PLP Architecture (Founding Partner)

Kiru Balson, Building Research Establishment (Chartered Architectural Technologist)

Richard Bates, alinea Consulting (BIM Manager)

Graham Brierley, Laing O'Rourke (Head of Digital Engineering)

Steven Cairns, Leica Geosystems Ltd (Geospatial Consultant)

Will Davies, Verisk Geoinformation (Buildings Project Manager GeoInformation)

Chris Going, Verisk Geoinformation (Senior Analyst)

Josh Goodwin, SDC Builders Ltd (Project Design Manager)

Scott Harden, Enable My Team (Digital Delivery Manager)

Luke Holbrook, Enable My Team (Digital Delivery Manager)

Zelda Kaitano, alinea Consultants (Quantity Surveyor)

Simon Morrall, SDC Construction Group (Commercial Manager)

Ruth Norman-Johnson, Ramboll (Digital Projects Manager)

Alex Palmer, Smith and Wallwork (Head of Digital Engineering)

Kyle Peters, Buckingham Palace Reservicing Programme (Senior Project Manager - Client representative)

Stefan Schmidt, Hoare Lea (Performance Engineer)

Richard Saxon, CBE, Consultancy for the Built Environment (Principal)

Gwilym Still, Max Fordham LLP (Engineering Project Leader, Passivhaus Consultant, Partner)

Appendix D

Research theme	Group Identifier	Capability Summary We need to know how to...	Impact 1 – Low 5 - High	Research Needed 1 - Low 5 - High	Category coding	Risks and barriers
Information management and sharing	1	transfer between design, construction, facility management team	5	5	IM1	
	1	optimise occupier performance with building performance - proving the business case for the asset, full digital twin	5	4	O2	
	1	use the previously collected and generated data to improve future designs	4	2	IM4	
	1	share data with the wider community to allow lessons learnt to be drawn out and benefit the whole industry - learning for the greater good	4	2	IM4	
	1	use the data that we have on previous designs to make future designs better	4	2	IM1	
	1	access data through the whole life-span of the building and not just during the project	2	2	IM1	
	1	manage control of data to address ownership, privacy, security	3	1	IM4	R2, R3
	2	decide where the cost of establishing and operating a project information management system should lie	1	2	IM1	B1
	2	represent flexibility and uncertainty in early stage designs to aid coordination and design development	1	4	IM3	
	2	implement parametric testing and iteration into more projects for optimisation and reduction of repetitive tasks	2	3	D1	
	2	close the skills gap between facilities managers and the systems being put in to buildings, possibly by centralising FM	2	3	B4	
	2	digitise commissioning data and achieve auto-commissioning	4	1	D2	
	2	define and share data ownership, trust and risk	3	4	IM4	B1
	2	efficiently produce "live" costing from data/models (Trust issues)	5	1	IM1	B1
	2	bring structure to unstructured data, such as implementing industry naming conventions for assets	5	2	IM1	
	2	effectively share modelling data to avoid rework, including programming interfaces and access permissions issues	5	3	IM4	

	2	achieve a system of right data and right time, by understanding what each stakeholder needs at which points and ensuring data reliability, format, accessibility	5	5	IM4	
Data-driven decision-making	3	create risk assessments for communities based on past damage events e.g. decisions based on flood risk maps	2	2	IM5	
	3	define the data required/useful to the decisions we need to make and allow freedom for the data to inform	3	2	IM1	
	3	encourage whole life approach to construction projects, linked to upfront costs	4	2	IM2	
	3	use data to analyse and understand what a client really wants, rather than what they think they want	4	4	IM1	
	3	have access to existing building/historical data to make better decision-making inc. building options and future performance	4	4	IM4	
	3	trust the data and the integrity it can provide whilst maintaining the skills/experience competencies in order to see beyond outputs	5	5	IM1	B1
	4	standardise product data, make it contemporary and comprehensive	5	5	IM1	
	4	agree data requirements for multiple stakeholders, so all parties have the data they need for decisions	5	5	IM4	
	4	record mistakes and learn from past mistakes	5	4	IM4	
	4	use modelling & simulation to inform decisions (foreseeing outcomes of decisions at an early stage)	5	3	D1	
	4	keep data up to date in a cost-effective way (as buildings are adapted over time)	4	5	IM6	
	4	present, absorb and understand data easily	3	1	IM1	
	4	make decisions with data streams of differing quality and uncertainty	3	5	IM3	
As-is reality capture	A	collect as-built data about fabric and services in existing buildings	5	5	O2	
	A	prioritise and apply cost-benefit evaluation to alternative data collection exercises	4	4	IM1	B3
	A	ensure compatibility of data, e.g. by data exchange formats	4	4	IM1	
	A	determine as-built U-values	3	5	O2	
	A	make reliable inferences about building fabric and services from data about building types	2	5	O2	

	A	classify existing buildings into types	2	2	IM5	
	A	update design stage BIM files when building construction is completed, to pick up variations especially in services	2	1	IM6	
	A	ensure long-term access to data, e.g. avoiding technical obsolescence of database system or termination of access to proprietary data	3	1	IM6	R1
	B	use sensors to find out if the loading predicted and the structural behaviour assumed are realised	2	3	O2	
	B	collect 3D models of entire existing uk building stock remotely	3	4	IM5	
	B	collect intrusive survey data without the obtrusion	4	4	A2	
	B	capture existing utilities underground, application of GPR is overlooked and not widely known	4	3	A2	
	B	agree as a project team, who needs what, defined with more precision than just LOD and LOI	3	1	IM3	
	B	get contractual commitment on the materials information captured in the survey data	3	2	IM4	B1
	B	transfer point cloud from the field to the office in real time (5G)	3	3	A1	
	B	get access to technology that we cannot afford to buy i.e. rental schemes. purchasing the technology or purchasing the service are not working. want ownership of the data collection, but without the capital outlay	4	1	B2	
	B	integrate in-use performance at design stage, understand who needs what when and why	4	2	IM2	
	B	integrate point cloud survey with drone data to create live as-built data	5	5	A1	
	B	get measurements from laser scanning data in real time in the field i.e. rapid processing of data	5	5	A1	
	B	manage the size of the point cloud data files, either reduce file size, collect less data, or increase processing power	5	5	A1	
On-going reality capture	C	quantify and review cost-benefit at the end of a project to inform future projects	2	2	O2	
	C	create a framework for data usage (what should we collect, how should we collect it, what should we use it for) for operation life-stage	3	2	IM1	
	C	measure, quantify and communicate uncertainty in the performance of a design and all its systems	2	4	IM3	

	C	create trusted and useful models by defining what users want at early stage to capture correct data only	4	2	IM1	
	C	ensure "hardware" or physical assets are flexible to "software" or "tech" upgrades in the system (ensure longevity of physical assets)	5	3	IM6	R1
	C	identify and implement most effective feedback loops both with and between life stages (e.g. what operational data can inform design early on?)	4	3	IM1	
	C	achieve occupancy optimisation through the integration of "experiential" and "physical" data analysis	5	4	O1	
	C	ensure model usefulness through life by understanding what it should contain and who will need to use it (lean principles)	4	5	IM6	
	D	create new tenancy agreement models to reduce tenants end-of-tenancy costs on upgrades	1	1	Other	
	D	embody and quantify environmental and social benefit into financial business model	2	2	Other	
	D	develop a shared view of how FM can deliver "top-line", not just cost reduction	3	1	IM4	
	D	create a complete building class analysis	3	3	IM5	
	D	rethink the concept of space as a service, given data capture analysis to optimise it	3	3	O2	
	D	create standards for usage data collection, including sensoring equipment to ensure a base level of accuracy	3	5	O2	
	D	create material passports (performance data collection) in particular a need for non-residential log books	5	3	O2	
	D	create new business models which distribute risk across stakeholders and support effective facilitating workspace management using data from building and organisational performance	4	4	Other	B1