Centre for Digital Built Britain

CDBB Research and Development Landscape Review

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UNIVERSITY OF CAMBRIDGE

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Executive Summary

This review of CDBB funded literature revealed a wide array of tools - meaning digital technologies, processes and frameworks - at various stages of maturity, many of which could be transformative if they were widely adopted. However, there are barriers to this adoption in the level of readiness of many of the tools, as well as the readiness of the industry to take them on. This project categorises maturity on a spectrum from green to red, revealing where these tools need further development, versus where their adoption is blocked by structural barriers.

Several research priorities emerged as common across multiple projects, or as enablers for the adoption of current research, including the design of user interfaces for these digital tools; scaling up of what is being done already to larger areas, more heterogenous data or to more complex areas; exploring barriers to and drivers of adoption; and improving functionality of the tools themselves. Most of the tools reviewed here would benefit from some iteration, development or further research.

But research and development alone do not guarantee adoption by industry of these tools. The remedies to structural barriers need to be put in place in order to create an adoption pipeline. These include enablers such as management buy-in, case studies, skills development and creating roles within organisations that help facilitate individual ICT literacy journeys. The research priorities and recommendations are summarised here and at the end of this review.

Research priorities

- Developing user interfaces and visualisations that communicate **uncertainty, data quality** and provide helpful **insights**;
- **Scaling up** existing data and systems integration, digital twin and predictive modelling technology in various contexts;
- Continuing to explore **social, structural and political** barriers to and drivers of technology adoption;
- Continuing to explore techniques for **automated data quality assurance, classification and identification** to reduce the volume of specialist work needed at the front-end of every digitalisation journey;
- Improving the **reliability of predictive modelling**, including with fragmented data, for factors such as building and service performance, life-cycle assessment and impact on environmental systems;

- Exploring issues around **social acceptability**, such as trust in experts and privacy, both through traditional academic research and co-design projects, to find out what people do and do not want from a digital built environment.

Recommendations

- Continue to **explore the integration of BIM** with processes and contexts beyond design and build;
- Integrate technological innovations with existing or novel **user-friendly tools**;
- Fund and promote studies that **demonstrate the business cases** for these tools;
- **Integrate these business cases** with, and extend the scope of, existing resources such as the Scottish Futures Trust BIM ROI calculator[1];
- Encourage experimentation by organisations and local authorities with early prototypes, in collaboration with the DT Hub;
- Publicise **models of technology adoption from industry leaders**, highlighting success strategies such as:
    - Writing a **digital strategy** that guides how digital technology and information management will be used to create value for the business, its employees and the public;
    - Adopting and advocating for the **Gemini Principles** as a means of doing so;
    - Creating roles within organisations that **specialise in the integration of BIM** and other technology with existing tools and processes;
    - Providing **individualised ICT skills training** and support that meets employees where they are in their digital literacy journey;
- Promote business models and policies that ensure people will not lose their jobs to automation, and communicate transparently about changes to the future jobs market;
- Embed digital skills into education throughout the disciplines, and encourage the development of a more interdisciplinary-focused educational sector.

Introduction

This paper reviews the existing research and development landscape within CDBB-funded research, and highlights where tools – meaning digital technologies, processes or frameworks - exist that could easily be adopted by industry, and where further structural and academic work is needed. The first section discusses the method used to categorise the literature and the second gives an overview of the tools featured in this literature, explaining why they fall into those categories. The third section discusses common barriers and enablers to technology adoption in the built environment lifecycle sectors. The paper ends with conclusions about research priorities and recommendations.

1 - Method

[1] https://bimportal.scottishfuturestrust.org.uk/page/roi-calculator

This review covers CDBB-funded general research projects, mini projects, early career research projects, tendered projects and research networks from 2017-2019, as well as recent publications by CDBB's most closely related research groups at Cambridge, the Centre for Smart Infrastructure and Construction (CSIC) and the Institute for Manufacturing (IfM). The classification is based on a contents analysis[2], using evidence from the text to sort the tools they discuss into categories:

- **Green**: Technology or tool is ready for adoption. The primary barrier is knowledge of its existence, and potentially minimal cultural barriers where evidence of value and good practice could sway opinion.
- **Green/Amber (edge cases)**: While the tool appears to work and is potentially being used by some industry leaders, there are still some structural barriers to its use by the rest of the sector.
- **Amber**: While the technology or tool exists and could be ready for adoption, there are major structural and cultural barriers in industry that need to be addressed.
- **Amber/Red**: The technology or tool needs more research and development before it can readily be adopted by industry. Future research recommendations identified by the papers' authors are provided.
- **Red**: There is a combination of structural barriers and remaining research gaps preventing adoption. Further research should explore ways of making the tool applicable, iterate it, expand it, and/or recommend which governance structures and social levers could be used to facilitate its adoption.

A brief overview of how the reviewed papers fall across these categories is provided here, and there is further discussion about each of the categories and the justification for the categorisation in the next section.

It is important to note that there are potentially transformative tools throughout this spectrum, so a strategy that simply picks up on the work categorised as green because it is perceived as easier to adopt would be missing out on valuable opportunities. The value and transformative nature of these projects is not provided here, because depending on how they fit together any of these projects could create tremendous value. Section 2 provides more discussion of each project

Categorised papers in this review

Citation	Description of Tool
Allmendinger & Sielker, 2018	BIM for urban planning
Blay et al., 2019	Framework on information resilience
Construction Innovation Hub, 2019	Scottish Futures Trust Infrastructure Technology Navigator
Dent & others, 2019	Map assessment criteria for complex projects to BIM
Juan et al., 2019	Framework for balanced scorecard approach to evaluate automation in construction

[2] This work was not reviewed by a subject expert, so this is based on a generalist view using only the evidence provided in the text of each paper. The categorisation was subjective based on textual clues and the impressions of the reviewer from those clues.

Ramage et al., 2018	Autonomous image recapture of existing assets using historical illustrations or photos
Zomer et al., 2020	A model for change toward BIM in organisations
Citation	**Description of Tool**
Alwan, 2019	Digital Energy Estimation Tool
Brackenbury et al., 2019	Classification for masonry bridges
Gürdür et al., 2019	Process and visualisations for the assurance of data quality
Jalia et al., 2018	Smart building technology – The Edge, Amsterdam case study
Martinez et al., 2019	Digital twins integrated with business models
Palau et al., 2018	Exploiting traffic data to improve asset management and citizen quality of life
Wan, 2019	City-level digital twins for transport
Citation	**Description of Tool**
Burgess, 2018	Digital decision support for planning
Burgess, 2018	Offsite manufacturing for housing
Burgess, 2018	Technology for in-home care
Heaton & Parlikad, 2019	Smart City Framework
Konstantinou et al., 2019	Tracking multiple construction workers on-site using computer-vision
Lindenthal & Johnson, 2018	Machine Learning and AI to categorise building type to estimate price
Luo, 2019	Aerial Swarm Robotics for active inspection of bridges
Madhavapeddy et al., 2018	Operating System for Interspatial Networking
Muir & Burgess, 2019	Digital technology for private rented sector
Rosenberg et al., 2019	Toolsets to support and integrate digital planning into programme management and operational activities
Sielker et al., 2019	City Information Modelling (CIM) for responsible cities
Citation	**Description of Tool**
Agarwal & Bance, 2019	Interactive wearable smart acoustics
Boehm, 2019	Synthetic point cloud dataset than can automatically generate tags to populate digital twins
Dent & others, 2019	Decision support tools that model and visualise uncertainty
Heaton et al., 2019	Developing BIM models and handover tools to support operations and maintenance
Jin et al., 2018	Method of calculating level of design / engineering for structural safety in uncertain conditions
Jin et al., 2018	PolyChora Alpha - Smart City digital interface
Lamb, 2018	Blockchain / smart contracts
Navarro et al., 2018	Building Impulse - novel building user experience metrics
Prorok, 2019	Co-development of autonomous vehicles with built environments
Stone et al., 2018	VR for designing safe complex environments, accessible VR
Ye & others, 2019	Digital twins for structural health monitoring of bridges
Citation	**Description of Tool**
Biscontin & Jin, 2018	Adaptive design of supported excavations
Bryden Wood, 2018	Platform approach to PDFM
Burgess, 2018	Housing governance that incorporates digital technology
Choudhary, 2019	Standard procedure combining statistical models of energy use to help planners understand a target area at various levels of detail
Davila & others, 2018	VR and AR tools and technologies for built environment sectors
D-COM Research Network, 2019	Digital compliance checking
Eckert, 2019	Decision support tool that uses data and simulation to understand future demand when specifying systems, striking the contextually appropriate balance between under- and over-engineering

Junior et al., 2020	Automated system based on semantic framework for checking compliance with regulations and building codes on complex projects
Whyte et al., 2019	Decision support tool that can model interdependencies in complex projects
Zomer, 2019	BIM for operations

2 - Discussion

Tools

The tools discussed throughout CDBB-funded work vary widely in their complexity and readiness for adoption. As discussed above, the term "tools" is used here to mean digital technologies, processes and frameworks. As an interdisciplinary centre, the work covers tools developed from a variety of different perspectives. Each one of these projects contributes to a broad vision of the future relationship between digital technology, data, organisations and people in the built environment, the details of which are still a matter for research and development in academia and industry.

Green

In this category, the technology or tool is ready for adoption. The only barrier is knowledge of its existence, and potentially minimal cultural barriers where existing evidence of value and good practice could sway opinion.

Citation	Description of Tool	Justification
Allmendinger & Sielker, 2018	BIM for urban planning	This paper recommends policy ideas that could be implemented right away. It touches on multiple bi-partisan policy priorities so there should be few barriers to its implementation.
Blay et al., 2019	Framework on information resilience	This framework is ready for adoption into standards but could benefit from some case studies of its use in context.
Construction Innovation Hub, 2019	Scottish Futures Trust Infrastructure Technology Navigator	This tool exists and can be used already, it just needs to be publicised and added to as technologies – and the business cases for them – are developed.
Dent & others, 2019	Map assessment criteria for complex projects to BIM	One of the simplest steps to help complex projects function is for appointing parties to set the criteria for success in alignment with the UK BIM Framework.
Juan et al., 2019	Framework for balanced scorecard approach to evaluate automation in construction	This framework is ready to deploy in order to help with decision making about automation, but it would take some publicity and awareness building to ensure people know how and when to use it.
Ramage et al., 2018	Autonomous image recapture of existing assets using historical illustrations or photos	This tool is primarily useful in a research context, or for managers of historical assets. It represents a low-cost alternative to point cloud scanning that appears to work well as described in this paper.
Zomer et al., 2020	A model for change toward BIM in organisations	This framework is ready to deploy in order to help understand the change process toward BIM in organisations.

Among the easier to adopt tools there are extensions of existing frameworks, processes and technologies, such as using existing BIM processes in the context of urban planning. The delivery of national planning policy through BIM is considered to have medium potential for improvements in housing supply, reducing waste and better coordination, while there is high potential for BIM to optimise supply and shape demand in the planning sector. (Allmendinger & Sielker, 2018) The barriers to adoption are low, but a mandate from government would help ensure that any inertia or reluctance is negated. Similarly, using BIM to guide assessment criteria would be potentially transformative during complex projects, and that could be done immediately if appointing parties recognise the value of doing so. Dent & others (2019) discuss the importance of defining success and failure of these projects by terms that are more inclusive and descriptive than simply "on time and under budget" and instead using more detailed success criteria based on the UK BIM Framework.

A few projects applied existing technology in novel ways that could be replicated by anyone wanting to adopt them. For example, the autonomous image recapture project developed previous work to create a process that uses historic images to recreate viewpoints of buildings. This enables comparison with modern images and can help highlight how the built environment has changed over time. (Ramage et al., 2018) This primarily has application in the research context, but owners and managers of legacy assets might also find it useful, and it is ready to go, provided they can hire in or already have sufficient technology expertise to recreate this process. Finding organisations that are willing to experiment with this technology may help demonstrate its utility more broadly than simply publicising the research outputs.

Another category of ready-to-implement tools are some of the frameworks featured in this body of work (e.g. Juan et al., 2019; Zomer, 2019; and Blay et al., 2019). These are mostly based on literature reviews, but it is not clear from the reviews whether these frameworks are novel in terms of standards and practice in industry. Upcoming standards are addressing information resilience, for example. If these frameworks are ahead of the curve, however, they could be used in advance of relevant standards, and even inform those standards.

The easiest to adopt from this cohort of projects is the Infrastructure Technology Navigator, created by Scottish Future Trust and written up by the Construction Innovation Hub (2019). This tool helps match digital technology with needs for the built environment sectors and provides evidence of ROI and investment considerations. It also includes information about what digital skills are needed in organisations to adopt these technologies and the software and hardware requirements. This tool is available to use now, and simply requires expansion as technology develops, as well as publicity to ensure that people find out about and use it.

Green/Amber

While the tool exists and is potentially being used by some industry leaders, there are still structural barriers to its use by the rest of the sector.

Citation	Description of Tool	Justification
Alwan, 2019	Digital Energy Estimation Tool	The tool described in this paper seems to work but requires user feedback and further iterations to refine it before wider adoption.

Brackenbury et al., 2019	Classification for masonry bridges	Classification and structured data is essential to a digital built environment, but usually requires front-end effort by people with the right skills, working to a common, interoperable framework.
Gürdür et al., 2019	Process and visualisations for the assurance of data quality	Data quality assurance is another underlying challenge that is essential to a digital built environment, but there is a need to have people with the right skills to implement and develop the empirical rules to make this process work
Jalia et al., 2018	Smart building technology – The Edge, Amsterdam case study	The tools and technologies used in this case study were enabled by a highly motivated client. Others may require more evidence of value before adopting.
Martinez et al., 2019	Digital twins integrated with business models	There are examples of good practice in all of the business models discussed in this paper, but there are structural barriers preventing wider adoption.
Palau et al., 2018	Exploiting open access traffic data to improve asset management and citizen quality of life	This tool based on existing data sources and technologies, but combines them in a novel way, and demonstrates the value of bringing data together. However, work is needed by data literate people in industry to develop data analysis with a purpose in order to realise this value.
Wan, 2019	City-level digital twins for transport	This paper outlines several areas that need further research, but cities can use existing tools for transport planning in order to capture value.

These tools have either been partially implemented already or are relatively easily to implement, but some barriers exist, whether that's the need to demonstrate the business case or the need to conduct user testing.

In the case of the Edge building in Amsterdam, a novel configuration of BIM for operations and various IoT tools have been used in the final building. The project benefited from the enthusiasm and willingness of the client to invest in these tools (Jalia et al., 2018). Projects like this show the art of the possible, but more work is needed to demonstrate the long-term benefits of these innovations to those who are less willing to invest. Similarly, Martinez et al. (2019) outline various implementations of digital twins with different real-world business models. The businesses explored in this paper are leaders in their sectors, so more work is needed to bring the rest of the built environment sectors along, particularly by demonstrating the long-term investment case.

Another BIM-centred project, the Digital Energy Estimation Tool (DEET) project, "developed a unique parametric design based methodology for estimating total energy use in a building utilising BIM … frameworks and protocols." The aim is to integrate life cycle assessments of energy consumption with BIM to generate parametric models of energy use. This helps reduce the whole life carbon footprint of buildings at the design stage. This tool would benefit from user feedback and further iteration, but is otherwise easy to adopt alongside BIM for operations (Alwan, 2019).

Some of the papers in this category used existing tools in a novel way. For example, Palau et al., (2018) used Google's Directions API, Static Maps API, Python and other open source tools to make a decision-support tool for planning transport and housing. While they provided a demonstration that such tools can be useful, they point out that further testing is needed to see whether these tools can be scaled up to more complex problems. In a similar project, Wan (2019) developed a city-level digital twin for Cambridge focused on transportation policy in the medium- and long-term. Both of these projects underline that existing tools can be adapted as an early prototype for a city-level digital twin, and although more iterations are required to develop fully-fledged, fully functional and secure city-level digital twins, these prototypes can already provide interesting insights into the development of the built environment.

The Centre for Smart Infrastructure and Construction (CSIC) produced studies about two tools with a common barrier to adoption: having the right skills in place. Whether it is developing a classification system for masonry bridges to detect structural defects (Brackenbury et al., 2019), or assuring data quality from heterogenous sources (Gürdür et al., 2019), the underlying building blocks of a digital built Britain are enabled by some degree of front-end work to create the classifications, ontologies and empirical rules, and to identify where tools like connected digital twins would create value. This requires people with specialist skills, working to a common, interoperable framework and based on a common set of principles, to be in place across the built environment life-cycle sectors. While these structural barriers are blocking the majority in these sectors from adoption, the organisations that are getting it right are prioritising these front-end skills and specialist integrator roles, as explored in the final section of this paper.

Amber

While the technology or tool exists and could be ready for adoption, there are major structural and cultural barriers in industry that need to be addressed.

Citation	Description of Tool	Justification
Burgess, 2018	Digital decision support for planning	The technology exists, but the structural barriers come from the complexity and fragmentation of the sector. A strong mandate would be required.
Burgess, 2018	Offsite manufacturing for housing	The technology exists and the benefits are known, but there are many barriers to implementing it in the housing sector.
Burgess, 2018	Technology for in-home care	IoT technology could be easily adapted to this use, but more work is needed on social acceptability, governance and other cultural and structural issues.
Heaton & Parlikad, 2019	Smart City Framework	This framework expands on PAS 181 to include factors such as citizen requirements and the impact on those requirements of the functional output of infrastructure assets. This would need to be rolled into the Standards landscape.
Konstantinou et al., 2019	Tracking multiple construction workers on-site using computer-vision	While this method is effective, it requires more evidence to form a business case for adoption.
Lindenthal & Johnson, 2018	Machine Learning and AI to categorise building type to estimate price	Regulation and ethics around this technology needs to be considered before adoption, but it could be extended and adopted easily.
Luo, 2019	Aerial Swarm Robotics for active inspection of bridges	Machine learning and other existing technologies used in this project require specialist skills in industry, and there may be a lack of willingness to invest at this point.
Madhavapeddy et al., 2018	Operating System for Interspatial Networking	This paper presents a different theoretical model of networking in buildings. For it to work as

		designed, developers would need to create apps, meaning standards need to be created, and there needs to be a market for this model.
Muir & Burgess, 2019	Digital technology for private rented sector	While the technology discussed in this paper is relatively easy to implement, work is needed on building trust between tenants and digital tools that hold their data.
Rosenberg et al., 2019	Toolsets to support and integrate digital planning into programme management and operational activities	Other research throughout the CDBB programme has shown that existing tools can fill this role, although further development and iteration would be important. The primary barriers here are co-production skills, finding the right policy levers and developing a "digital social contract" that builds trust between citizens, industry and government bodies.
Sielker et al., 2019	City Information Modelling (CIM) for responsible cities	BIM needs to be scaled up to CIM, which does require some technological development, but the current barriers are things like data quality assurance, culture and business models, which can be addressed at least partially by structural changes.

Among the tools for which the barriers are primarily structural there is a wide range, from specific technological advances to theoretical frameworks.

Luo (2019) developed a novel technique for drones to fly in formation in order to inspect bridges with less disruption to commuters and less danger for inspectors. The technology would require specialist skills for use in industry, however, and as with VR and AR there may be a lack of willingness to invest at this point in time. Until these structural barriers are addressed, innovations such as this aerial swarm technology will not be picked up by the built environment sectors.

Konstantinou et al. (2019) use computer vision to track construction workers onsite using computer vision techniques in the interest of safety and productivity. This method does not require expensive or invasive hardware, nor does it require many person hours to be spent reviewing footage. In tests it performed better than the current state-of-the-art. However, there would likely need to be a compelling case made for investment in this technology based on evidence of use in situ.

Burgess (2018) gives an overview of several concepts around digital technology for the housing sector, including offsite manufacturing. While this technology exists, there has not yet been much investment in it and the financial barrier to entry into this market would need to be reduced for wider adoption. Burgess also discusses IoT-based care for older adults and Muir & Burgess (2019) discuss digital technology for the private rented housing sector, while Lindenthal & Johnson (2018) point to the potential for machine learning and AI to categorise and estimate price for the real estate sector based on photos of building facades. The barriers in each of these areas are the ethical and social acceptability of these technologies in and around housing and vulnerable individuals.

Some of the papers proposed sweeping ecosystems of technologies and processes for the built environment. Sielker et al. (2019), for instance, discuss the idea of responsible cities based on a scaling-up of BIM to city information modelling (CIM). As with BIM implementation, there are significant structural barriers, such as lack of collaboration, security and privacy concerns. In another dramatic change from the status quo, Madhavapeddy et al. (2018) propose Osmose, a platform- and app-focused method of customising user experience in the built environment. This is a shift from the current model built around devices connecting to centralised internet services and would require a substantial shift in the digital strategy and architecture of our smart buildings.

Amber/Red

The technology or tool needs more research and development before it can readily be adopted by industry. Future research recommendations identified by the papers' authors are provided.

Citation	Description of Tool	Justification
Agarwal & Bance, 2019	Interactive wearable smart acoustics	This technology needs more user testing and development before wider adoption.
Boehm, 2019	Synthetic point cloud dataset than can automatically generate tags to populate digital twins	The primary barrier cited in this project is simply developing the technology to extract individual objects using instance IDs. However, it would also need to be added to applications and tools to be adopted.
Dent & others, 2019	Decision support tools that model and visualise uncertainty	More research is needed into interactions in decision-making environments, capturing hard-to-quantify factors, and creating decision support tools that model and visualise uncertainty.
Heaton et al., 2019	Developing BIM models and handover tools to support operations and maintenance	The key barrier to adoption here is creating better improving functionality and usability for asset operators.
Jin et al., 2018	Method of calculating level of design / engineering for structural safety in uncertain conditions	This method would need to be integrated into design tools or applications in order to be useful in industry. Publicising examples of its use *in situ* to demonstrate the business case would also be important to adoption.
Jin et al., 2018	PolyChora Alpha - Smart City digital interface	This method of visualising city data is promising but needs more user testing and development.
Lamb, 2018	Blockchain / smart contracts	A great deal of work is needed to understand and demonstrate how distributed ledger technologies could be used in built environment sectors, and legal precedents for smart contracts need to be set.
Navarro et al., 2018	Building Impulse - novel building user experience metrics	Much more work is needed on passive metrics and technologies that utilise them. There is also social research needed into the ethics and social acceptability of passive metrics in the built environment.
Prorok, 2019	Co-development of autonomous vehicles with built environments	While the technology is promising, work is needed to scale it up to more complex and larger environments and improve the performance of automated sensing and decision making.
Stone et al., 2018	VR for designing safe complex environments, accessible VR	While this is a good proof of concept technology that inexpensively aids usability of VR, it has not been tested with its intended user group.

Ye & others, 2019	Digital twins for structural health monitoring of bridges	Further work is required to develop the methodology for suitability in different situations and to improve confidence levels.

These papers describe tools, technologies and processes that need more research and development before they are ready for adoption, including in several cases testing with different user groups or in different contexts.

One category that can be applied to this diverse range of tools is Internet of Things (IoT) technologies, from wearables to vehicles, that interact with the built environment in some way. Agarwal & Bance (2019) write about wearable technology that can sense the acoustics of a space and feed it back to hearing aids for hearing impaired users. This would need to be standardised to interoperate with existing hearing aids, and testing with the target user group is needed. IoT technology could also help co-evolve the built environment with autonomous vehicles using perceptive infrastructure. The project is ongoing and this paper points to various challenges of scale and complexity arising in this work that need to be addressed in the future. (Prorok, 2019)

Underlying IoT will need to be automated processes for identifying and tagging objects, events and people. One such process is discussed by Boehm (2019), who points to the possibility of datasets that can automatically generate tags to populate digital twins. The approach starts with an entirely synthetic environment, labelling and tagging various objects inside and outside buildings to create a dataset that can then train a machine learning algorithm to automatically generate those labels. This would save time in producing and populating digital twins of the built environment. However, more work is needed to develop the ability to tag more than one instance of the same type of item, and to integrate this process with digital twin tools and applications.

Human-Computer Interfaces (HCIs) also feature here, with multiple papers addressing this concept. With PolyChora Alpha, Jin et al. (2018) introduce a visualisation and modelling tool for integrating data about land use at the site level as a way of supporting planning decisions. The focus is on ease of use through techniques such as sliding bars to intuitively change parameters. The proposed tool has the potential to be very useful to the planning context, but a great deal of development is needed, both in expanding the volume and diversity of data types it draws on and in testing the tool with the intended user groups.

A similar research gap limits the VR implementation proposed by Stone et al. (2018). Their paper discusses a prototype for a low-cost, high fidelity VR system using readily available hardware to increase the usability of VR for individuals with balance and sensory impairments. Their final use case would be to facilitate participation by these individuals in the design of the built environment to enable them to navigate these environments more adeptly. While the prototype worked well, they had not yet tested it with this user group. This is a gap facing many of the tools and technologies discussed in this review, particularly those that have an interface between humans and data: that greater testing with a wide range of users is important to ensuring digital built Britain develops in a truly inclusive manner.

In the interest of supporting the interface between humans and data, Heaton et al. (2019) outline a novel methodology for extracting BIM data into a relational database that can then be used with existing asset management systems. Previous work in the area had identified skills as a barrier to adoption. Rather than focusing on upskilling the audience, however, this paper advocates creating more user-friendly interfaces for the technology. Their novel approach can operate behind the scenes without needing to convince anyone of its utility or teach them how to use complex classification schemes, provided it enables usable, functional tools. Again, user testing is needed here.

With a similar user-friendly approach in mind, Jin et al. (2018) developed a proposed user interface (UI) for smart city design, “for visualising in 3D animation the combined urban land use, buildings, transport infrastructure and associated urban services.” This UI would be an intuitive way for users to tweak parameters and see the effects in graphical form rather than looking at raw data. In the planning context, it would support, “integrated design of alternative scenarios of urban land use, transport systems, buildings and infrastructure projects.” An alpha version of the underlying analytics tool is currently being used in a pilot with Cambridge and Peterborough Futures, a modelling study funded by two local authorities, but it lacks the proposed visualisation and requires specialist knowledge to use the current interface. They point to the need for further work to iterate the interface, create the visualisation aspect of the tool and test it with non-specialist users.

Another aspect of such interfaces is the need to communicate clearly about uncertainty in the data and models. This has been addressed by one of the CDBB research networks, who pointed to several aspects of uncertainty that require considerable further work, including building an interdisciplinary research base exploring interactions in decision-making environments, ways of tracking hard-to-quantify factors and decision support tools that model and visualise uncertainty in meaningful ways (Dent & others, 2019). They call for a balance between case-by-case flexibility and standardisation, and better contractual structures that take uncertainty into consideration and enable digital compliance checking under these circumstances. These lay the groundwork for specifying future research and development, but are not currently in the realm of reality.

The Building Impulse project addressed the issue of hard-to-quantify factors through user developing surrogate metrics that stand in for occupant satisfaction, productivity and wellbeing. Navarro et al. (2018) developed a toolkit that used environmental monitoring alongside high frequency occupant feedback, in the form of a polling station that prompted them to give feedback every two hours, and indirect systems for capturing satisfaction, such as heart rate and facial expression. Further research is needed to develop and align the active and passive user feedback, but also to explore how socially acceptable that level of passive monitoring would be to the wider public in light of its benefits. This is just one approach to hard-to-quantify metrics, and there are many others that would be worth exploring to better assess complex projects.

Another paper highlighting the need for further research explores digital twins for structural health monitoring of bridges (Ye & others, 2019). They outline a framework for real-time data management using BIM, followed by a series of physics- and data-based approaches to checking the validity of simulations and the quality of the data. This framework was tested with real-world bridges to determine early performance in ways that enable long-term condition monitoring. While this method was effective in this sample, further work is needed to develop the methodology to integrate more heterogenous datasets into a working digital twin that could be connected with other digital twins.

The final paper discusses a technology about which there has been considerable hype, including in the built environment sectors. Distributed Ledger Technologies (DLTs), of which Blockchain is the most well-known example, have been heralded as transformative in just about every sector. Its most logical application in the built environment is in digital compliance checking, which came up in the previous category as a concept that needed considerable work. While DLTs are promising for their security and transparency relative to other smart contract methods, their legal status still needs to be determined and it is likely that there will need to be multiple demonstrations of the business case before they are adopted. There is also an urgent need to develop competencies in this area throughout the built environment supply chains in order to make DLTs a viable method of compliance checking. (Lamb, 2018)

Red

For these tools and technologies, there is a combination of structural barriers and remaining research gaps preventing adoption. Further research should explore ways of making the tool applicable, iterate it and/or recommend which governance structures and social levers could be used to facilitate its adoption.

Citation	Description of Tool	Justification
Biscontin & Jin, 2018	Adaptive design of supported excavations	While the tool is viable as described, there are various technical and contract-related issues to work on, and a business case would need to be made for its adoption.
Bryden Wood, 2018	Platform approach to PDFM	The technologies and processes described in this paper are potentially transformative and there is work on many of the elements. However, getting the built environment sectors ready to adopt simultaneously would be difficult.
Burgess, 2018	Housing governance that incorporates digital technology	This paper highlights some issues for government to address regarding technology to support housing. Technology and regulations to assist retrofit of homes to be 'smarter' and more efficient should be a priority, as should decision-support tools to give a clearer overview of the fragmented housing market.
Choudhary, 2019	Standard procedure combining statistical models of energy use to help planners understand a target area at various levels of detail	The paper points to several technical and structural areas that need further work: developing a framework to include patchy data scenarios, comparing UK cities and towns to create clusters of similar energy use behaviours, combining information at scale as proof of concept and testing with users to prove knowledge sharing hypothesis. Having a master planning system that can draw on interoperable data from UK cities and towns is essential.
Davila & others, 2018	VR and AR tools and technologies for the built environment	Lack of specialised AR and VR technology for the built environment sectors is a major barrier. Culturally, immersive technology is seen as superficial rather than a sound investment.
D-COM Research Network, 2019	Digital compliance checking	There is the need to develop standards and skills, as well as software and hardware, around digital compliance checking. The priorities for technology development should be for software that is simple,

		automated and interoperable with the tools that are already pervasive in the built environment sectors.
Eckert, 2019	Decision support tool that uses data and simulation to understand future demand when specifying systems, striking the contextually appropriate balance between under- and over-engineering	Changing procurement structures for large organisations like the NHS would help break their tendencies toward under- or over-engineering. While this is an important development, better monitoring and data capture are needed to model current systems to understand the changing demand side.
Junior et al., 2020	Automated system based on semantic framework for checking compliance with regulations and building codes on complex projects	Further technical work is needed to embed this semantic framework in decision tools, and there is a need to check other regulations against the developed taxonomy for validation. Structural work should explore the relationship between client needs and the regulatory environment.
Whyte et al., 2019	Decision support tool that can model interdependencies in complex projects	Sharing data across organisational boundaries is a barrier here, but there is also a challenge in making complex modelling technology accessible and available to infrastructure decision makers. Further research should focus on discovering and modelling unknown interdependencies and emerging complexity.
Zomer, 2019	BIM for operations	While there are a number of cases, like this one, that point to the use of BIM in the operational life of an asset, there needs to be more work on structural barriers and more published case studies to make the case for it sector-wide. Future research could revisit these early implementations of BIM for operations to get longitudinal data on user perspectives and real-world performance.

The majority of the papers in this category explore broad ecosystems of processes and technologies that are in various stages of maturity and need to be further iterated, demonstrated or mandated in order to be adopted.

While BIM for operations has already been demonstrated by several successful case studies, for example (Zomer, 2019), the sectors involved still tend to operate in silos and adoption is limited to more motivated clients. Longer-term data is needed to make a better case for investment, and research that continues to explore policy and social levers would also be useful.

Similarly, immersive technologies such as VR and AR are already used to create value for a small number of leaders by facilitating the design process, helping client engagement and as outreach tools. In this case there is an acceptance by industry that they will eventually need to adopt AR or VR, but that has not resulted in actual investment to date. Davila & others (2018) outline the need for an R&D road map to target investment and research in the right areas when encouraging the built environment sectors to adopt AR and VR. They note that while technical limitations may be the bigger barrier at the moment, eventual widespread adoption will be a matter of breaking down structural and cultural barriers, such as a lack of visible long-term gains resulting from using the technology.

A platform approach to design for manufacture (PDFM) would be a transformative tool in the built environment sectors, changing existing supply chains and workforces, and potentially bringing about profound gains in resource and time efficiency. Some of the component technologies are already being developed, particularly around modular construction using super components constructed offsite, the "factory in a box" concept and the underlying information management processes that help ensure consistent specification of parts. The barriers facing the sector-wide adoption of PDFM are similar to the barriers to digitalisation in general, which are discussed in the next section. They include cost, lack of incentives, developing interoperable systems and sub-systems and ensuring there are the right skills in the right roles throughout the supply chain. (Bryden Wood, 2018)

Two of the papers in this review look at digitally enabled governance structures around the built environment. Along with other issues discussed previously, Burgess (2018) describes a need for policy makers to balance housing pressures with other priorities such as environment, regional growth, transport and energy. This highlights the need for digital tools to help navigate these complex systems and give decision makers a clearer picture of the current state and potential future scenarios, but these tools need considerable development and user testing, as well as successful demonstrators.

The other governance-related paper, by the D-COM Research Network (2019), looks at digital methods of checking contractual, legislative and standards compliance. This, too, would potentially transform construction processes and reduce the need for time-consuming and costly work of manually checking projects are compliant with all relevant policies. The plan they set out to achieve this is ambitious. There are promising technologies in this area, but the security, transparency and reliability of digital compliance systems need to be demonstrated, iterated and proven at scale. The largest barriers, however, are structural; it could mean massive changes to the workforce, processes and supply chains in the built environment sectors, and therefore there will be reluctance to test out and adopt digital compliance.

Also in the realm of compliance checking, Junior et al. (2020) worked on recommendations for an automated system for checking compliance with regulations and requirements on building projects in the healthcare system. The propose a semantic framework based in BIM that would help ensure structured, machine-readable information is available for an automated regulatory review process. They conclude that, "a high percentage of qualitative requirements could be translated into logical rules by the proposed semantic approach", but that there are areas in which manual compliance checking would still be required. This would require technological advancements in machine readable building code models, as well as developments to the existing processes and regulations themselves to be able to interoperate with digital systems.

Innovations around planning tools appear frequently in this category of papers. Choudhary (2019) proposes a procedure for knowledge exchange between cities and towns, combining statistical models of energy use in order to help planners understand a target area at different levels of detail. This nationwide master planning tool would help facilitate knowledge sharing about effective policy- and technology-based methods of reducing carbon emissions from energy and planning for future low carbon energy needs. This process is based on the hypothesis that towns and cities with similar energy use profiles might benefit from sharing practice with one another. However, technical and structural work is needed to integrate this into the planning process and it also needs to be tested at scale with a range of different cities to validate the hypothesis.

Another paper focused on planning and decarbonisation comes from Eckert (2019) who proposes decision support tools and adjustments to procurement processes to reduce the under- and over-design of systems and assets. To develop this type of tool, better capture and modelling of current usage data and a clearer understanding of likely future growth would help drive predictive models that strike a better balance. However, the structure of procurement processes for organisations like the NHS, which seem to encourage less optimal outcomes, would also need to change for the full benefits to be realised.

One of the chief benefits of digital planning tools that draw on rich, well organised datasets would be the ability to model interdependencies in complex projects, and therefore predict the impact of design changes, material and timescale changes and other parameters on the finished project and the system in which it sits. Such a tool is proposed by Whyte et al., (2019), who explore its feasibility in a case study of the Tideway project. They explored ways of understanding and modelling interdependencies, looking at a series of questions about critical parameters, system health and the effects of late stage design changes, for example. They conclude that their numerical method was able to identify all the interdependencies in the project, and that given its low computational cost it could be scaled up to large infrastructure systems. This would help deliver on the promise of digital planning tools, but it does require both further research - in the form of identifying unknown and emergent interdependencies and developing linked data for digital twins at the city scale - and structural solutions in order to make these advanced modelling methods accessible and available to decision makers.

The final paper in this category looks at tools for dealing with uncertainty in building excavations (Biscontin & Jin, 2018). They use a Bayesian approach to predict soil movement based on all available data and to reduce on-site errors and time lost due to unexpected shifting. The prototype discussed in the paper sounds promising as part of a suite of digital tools to support construction, but it would need to be integrated with those tools and tested in practice. They also discuss the need for governance to help specify and mandate required metrics and models for decision making in construction.

The most broadly applicable discussion in this paper is about complexity in modelling, saying, "In order to develop the right tool, it is important to evaluate the point at which model complexity stops providing meaningful improvements to the decision-making process. … It also seems the complexity of the model may not necessarily enhance the confidence on decisions, whereas simplicity may facilitate understanding and more transparent decisions." This debate could and should take place across all the tools discussed in this paper. Identifying the point at which more data does not add more value depends on the circumstance, but it is an important part of digitalising the built environment sectors. As the authors of this paper argue, sometimes simplicity is more helpful for decision-making than complexity, as long as it can be achieved without losing transparency, and maintain a sense of how uncertainty impacts interpretation of the model.

For this reason, the adoption of any these tools needs to be facilitated by knowledgeable and information literate people working to a digital strategy and a set of guiding principles. Ensuring the purpose, trust and function (Bolton et al., 2018) of any digital tool used in the built environment lifecycle requires human decision makers to understand how digital technology does and does not create value.

Multifaceted maturity: the IfM digital twin case study

In reality, the categorisation used above oversimplifies the maturity of tools developed by research projects. This is particularly true at the leading edge of smart cities, connected digital twins and other complex integrated systems, where the developments are occurring in multiple different disciplines, and any one project may leverage multiple existing tools and advance multiple new ones.

This is true of a Cambridge-based case study on digital twins for the built environment (Lu et al., 2019). The initial study is a digital twin of the Institute for Manufacturing (IfM) building, with plans to expand to the West Cambridge campus and eventually the whole city of Cambridge.

The IfM case study breaks the digital twin of a building into a five-layer system:

- Data acquisition layer
- Transmission layer
- Digital modelling and data complementary layer
- Data/model integration layer
- Application layer

The innovations in this case were the **selection of sensors for the data acquisition layer** and new **data processing techniques at the data/model integration layer**. The sensor network was selected for its computational efficiency and its scalability, as the intention is for this digital twin to integrate with site- and city-wide digital twins in further iterations. While it still needs to be tested at scale, the technical specifications for the sensor network indicate that it will be able to function for a larger campus- or city-wide digital twin, meaning it would be classified as **green**. For the data model/integration layer, the project created two digital twin instances: one research-based twin created by the project team, and another commercial instance developed in collaboration with Bentley Systems, "for providing a mature product option in the future market." (Lu et al., 2019) They tested functions and services in their research instance of twin, and then were able to hand the results over to their industry partner for incorporation with the commercial product. This could be categorised as **green/amber**, or green if the resulting technology is shared open source.

Otherwise, the write up of this project points to a mature body of existing technology at the early layers. Sensor technology, wireless networks and techniques for digital modelling are readily available, though they need to be improved, tested at larger scales and integrated into existing processes. There are also technical solutions for integrating heterogenous data from a variety of sources, though finding solutions for the challenges of deduplication, differentiation and standardisation are priorities. The architecture for the digital twin itself is a relatively novel configuration of these new and existing tools. The main novel applications for this case were for as-is asset management monitoring and future performance prediction, but this structure needs to be tested at larger scales, meaning it is **amber/red** in its maturity level.

This project also positions itself within the Gemini Principles (Bolton et al., 2018), making it one of the earliest digital twin projects to do so. The Gemini Principles are ready for adoption, though there may be structural barriers that would need to be identified and overcome, giving it a status of **green/amber**.

This example shows how a single project may contain complex levels of innovation and maturity. This makes it difficult to highlight to industry what tools could easily be picked up and by whom.

Identifying barriers and enablers to technology adoption may help create a better pipeline from research and development to widespread use, as discussed below.

3 - Barriers and enablers

According to the government report, *Transforming Infrastructure Performance*, "Pockets of new technology use and innovation already exist, but the scale and pace of change is slow in the UK and abroad. The reasons for this include a lack of investment in capital and R&D, and the lack of standardisation. The government can be a driving force to address these challenges. Government is the largest single client for construction and infrastructure projects." (Infrastructure and Projects Authority, 2017) However, government mandates to digitise have not always had the desired effect, and may be a barrier as well as an enabler, as they contribute to the complexity of construction projects (Shojaei, 2019).

While several barriers were discussed in the previous section, it is worth looking in detail at what some of the most common barriers are to digitalisation in the built environment sectors, and looking at methods that have enabled the successful adoption of technology and tools. While there is obviously contextual dependency, some barriers are common across these sectors. In the case of BIM adoption, these can be broken down into structure, people, technology and task based barriers (Oesterreich & Teuteberg, 2019 *via* Shojaei, 2019 - see Table 1 below).

Table 1

Category	**Common barriers**
Structure	• Legal and contractual uncertainty • Lack of demand • Lack of awareness of BIM benefits • Lack of government incentives and regulation • Lack of necessity • Non-widespread use
People	• Resistance to change • Lack of expertise • Lack of skilled personnel • Lack of training • Lack of information sharing, collaboration and trust • Lack of management support
Technology	• Lack of standards and interoperability • Insufficient infrastructure • Complexity of BIM • Time-consuming adoption • Lack of applicability and practicability • Availability of BIM • Poor quality of the model information
Task	• High investment costs • Lack of proven benefits • Lack of investment capital

While many of these are discussed widely throughout the literature, it is worth discussing a few in more depth. First, Shojaei points out that digital skills are a key issue. There is currently a lack of training and it is proving difficult to recruit people who already have the requisite skills. “People’s preference to continue their old habits coupled with the fear of job loss can lead to various forms of resistance to implementation.” This suggests that one possible enabler of technology adoption is to provide clear assurances that innovation will not lead to job losses or lower salaries for existing or future employees, as well as providing and sign-posting training and support in the necessary digital skills for each role. The support of senior management is essential in the adoption of new technology, so making the case for investment to these individuals is vital. That relates closely to the technology category, where Shojaei notes that, “Perceived usefulness and perceived ease of use are the major variables that motivate users to employ an information technology or information system.” There is both a perception change and a business case facet to this challenge, as well as reinforcing the importance of user-friendly interfaces.

There are positive examples of which industry leaders should take note. In working with various construction firms, Shojaei noted various initiatives that had worked in organisations that had successfully adopted digital technologies (personal communication, 22 January, 2020).

Successful initiatives featured tailored training, delivered by someone embedded in the organisation. Rather than having an external consultant come to train everyone in BIM, for example, a local champion could provide bespoke training on how the organisation uses the processes and tools. This tailored approach was extended to include individualised, self-directed training for all employees, with the support of the local BIM co-ordinator. One-to-one sessions with this individual would enable employees to start their skills development journey where they were at, rather than having them jump in at the deep end by assuming a level of digital literacy that not everyone had. Informal drop-ins with food and drink encouraged people to get their questions answered and helped overcome embarrassment.

Finally, Shojaei noted that one need not teach everything to everyone, but rather it is better to have a clear competency profile written into role descriptions so that every employee knows what skills they are expected to have or tools they should take the initiative to learn about, with help from the BIM co-ordinator or a similar role. Having this structure of training and transparency around competencies written into a digital strategy was another important enabler of change. For SMEs, this level of strategic planning is even more important as there is not often scope for a dedicated BIM co-ordinator, digital strategist or similar.

Disseminating these tools throughout the sector is an additional barrier, and a great deal depends on the will of the client. In the current environment, clients that do not have a mandate to digitise are primarily interested in reducing time and cost and do not place a premium on downstream benefits created by using novel digital technology and tools. Educating and making a business case to clients, therefore, is equally important to convincing management within the sector. Shojaei discussed the need to get the everyone within the sectors to move and adopt technology at the same time because of the complex interdependencies between the various organisations at the different stages of the built environment life cycle.

Conclusion

Many promising new tools around digital data and information in the built environment have been developed and described in the reviewed body of work. Most of these innovations address some facet of how business-as-usual could be improved through new technology, or through more effective and unified processes and frameworks. However, until they are iterated, scaled up, integrated with user-friendly tools, mandated through standards or championed by clients or industry leaders, many of these will not have an easy journey to adoption.

Any digital tool, process or framework needs to be accepted by industry, which involves breaking down various structural and social barriers, such as skills shortages, lack of management buy-in, perceived complexity and inadequate functionality. The following research priorities and recommendations may help ensure that these tools are adopted more broadly as the reach maturity.

Research priorities

Much of the research funded by CDBB has explored cutting edge technology that requires further development before it is mature enough to be used in industry. The review found that the following research areas are overarching across multiple projects and will aid in the eventual adoption of these technologies:

- Developing user interfaces and visualisations that communicate **uncertainty, data quality** and provide helpful **insights**;
- **Scaling up** existing data and systems integration, digital twin and predictive modelling technology in various contexts;
- Continuing to explore **social, structural and political** barriers to and drivers of technology adoption;
- Continuing to explore techniques for **automated data quality assurance, classification and identification** to reduce the volume of specialist work needed at the front-end of every digitalisation journey;
- Improving the **reliability of predictive modelling**, including with fragmented data, for factors such as building and service performance, life-cycle assessment and impact on environmental systems;
- Exploring issues around **social acceptability**, such as trust in experts and privacy, both through traditional academic research and co-design projects, to find out what people do and do not want from a digital built environment.

Recommendations

None of the tools or technologies discussed will be adopted without a clear pipeline to industry, whether it's BIM or computer vision-based health and safety tools, meaning that strategies for removing barriers are of high priority. The following recommendations will help smooth the way for the appropriate adoption of technology by industry:

- Integrate technological innovations with existing or novel user-friendly tools;
- Fund and promote studies that demonstrate the business cases for these tools;

- Integrate these business cases with and extend existing resources such as the Scottish Futures Trust BIM ROI calculator[3];
- Publicise models of technology adoption from industry leaders, highlighting success strategies such as:
    - Writing a digital strategy that guides how digital technology and information management will be used to create value for the business, its employees and the public;
    - Adopting and advocating for the Gemini Principles as a means of doing so;
    - Creating roles within organisations that specialise in the integration of BIM and other technology with existing tools and processes;
    - Providing individualised ICT skills training and support that meets employees where they are in their digital literacy journey.

[3] https://bimportal.scottishfuturestrust.org.uk/page/roi-calculator

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