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Research Landscape:
Scoping Review

Kirsten Lamb, CDBB

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Research Landscape: Scoping Review

This paper briefly outlines the digital built Britain research landscape through 1) a scoping review and 2) a gap analysis of bibliometric, scientometric and literature reviews and roadmaps identified during the scoping review. While neither of these activities are exhaustive, they are indicative, and they inform the Capability Framework and Research Landscape work.

A comprehensive summary of the literature for such a diffuse subject area as that covered by the digital built Britain capability framework could fill several volumes. In order to keep this summary succinct and to highlight areas for further research, this scoping review focuses on synthesizing bibliometric, scientometric and literature reviews conducted by academics between 2015 and the present day and categorises the research gaps therein according to the capability framework developed by CDBB. Additional roadmaps identified by an earlier search and papers that contribute to a broad understanding of the dbB research space were included as well.

The **REVIEW** section highlights features of the gap analysis and discusses some of the findings. The **APPENDICES** provide detail about the methods, the search terms used and publishing patterns in this area, as well as the **GAP ANALYSIS** itself.

Review

The results of the gap analysis are summarized by the heatmap table below. Along the horizontal axis are the categories from the capability framework, while the vertical axis shows whether those categories were rated as red[1], amber[2] or green[3] by the reviewed papers. The method is described in **APPENDIX 1**.

Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context

Taking the number of articles identified in the gap analysis (**APPENDIX 4**), hotspots are identified in Value (red), Data and models (red and amber). Within this body of literature, many authors identify the Built Environment and Data as very active areas. While there are tricky problems, such as interoperability and managing legacy assets, there are large research communities working on them. There is little evidence in all three RAG levels for literature that ties services in with the built environment. However, this may be

[1] Criteria for red: Authors point to a major gap in the literature, maturity or capability.
[2] Criteria for amber: Authors point to gaps that may have some initial work underway, or where the size and maturity of the research community were not indicated.
[3] Criteria for green: Authors point to a large body of literature or a very active research community. However, more research may still be needed.

an artefact of the search method. There are nuances of subject within this heatmap that can be explored more deeply in the gap analysis itself.

The reviews consulted contained several common threads, discussed below. The papers discussed here point to trends within the literature, as well as showing where there are gaps for further research or the need for unifying frameworks and convincing demonstrators.

Value

Discussions about value from data are varied, but most of them point to the need for further research. For example, Günther et al. (2017) 'call for empirical research on cross-level interactions and alignment' as means of deriving value from big data. Other authors point to the need for demonstrators and case studies showing the value of digitalization and big data through qualitative and quantitative metrics (e.g. Matarneh et al., 2019) There is an active community discussing value derived from big data specifically, whether that is from the built environment or in other contexts (e.g. Saggi & Jain, 2018), as big data has the potential to fundamentally change decision-making, business models and various other mechanisms for creating value. A few authors point to the need for more research that creates demonstrators that digital technology is investible. (e.g. Abella, Ortiz-de-Urbina-Criado, & De-Pablos-Heredero, 2017; Airaksinen et al., 2016; Batista et al., 2017)

Many authors note that big data creates the opportunity to better understand, model and manage information about user needs (e.g. Costin, Adibfar, Hu, & Chen, 2018), while others warn against big data's tendency to erase individualism and create a monolith of 'users' with apparently identical needs. Cowley, Joss, & Dayot (2018) point to the idea of multiple 'publics' with different ways of engaging with the same digital built environment, while Vanolo (2016) suggests that there is an emerging body of literature falling between the celebratory and the apocalyptic that looks at the diversity of possible outcomes for citizens of smart cities. These authors point to different meanings of value for stakeholders with different interest sets, and this diversity needs to be managed to create a robust understanding of how to measure and deliver value.

While it is important to demonstrate that creating, managing and sharing data is investible (Andriamamonjy, Saelens, & Klein, 2019), value is more than just return on investment, growth or profitability. There are human dimensions to value as well. Making subjects such as ethics, dignity and social outcomes a part of engineering and software design is essential if they are to be more than an ineffectual afterthought. According to Mahieu, van Eck, van Putten, & van den Hoven (2018): 'As long as core values such as human dignity are not translated, applied and specified at a concrete level where they can be used as functional requirements for the systems that are being built, we cannot expect them to become part of these systems in any meaningful way.' This means that the value of a smart built environment is contingent upon investment in and inclusion of human, social and natural resources in the systems that design, govern and create it. (Caragliu, Bo, & Nijkamp, 2011)

Frameworks

Throughout the literature there is broad support of frameworks as a way of measuring how well value is being achieved, and there is plenty of initial work to scope and create them, but less effort to empirically test, evaluate, join-up and agree on them. Indeed, the European Innovation Partnership on Smart Cities and Communities (EIP-SCC) point to a lack of standardized smart city indicator frameworks that can be used to compare global initiatives. 'A big challenge therefore is to determine the value of smart urban developments and to evidence the impacts on city outcomes.' (Caird & Hallett, 2018) Current smart city frameworks could provide some of the qualitative and quantitative metrics, and there are many to choose from, including: managerial frameworks for BIM (He et al., 2017); frameworks for developing new business models around big data (Zaki, Feldmann, Neely, & Hartmann, 2016); frameworks for managing big data attributes (Saggi & Jain, 2018); and frameworks for factoring in residents' wellbeing to smart city evaluation (Lin, Zhao, Yu, & Wu, 2019).

Other suggested frameworks include: a legal framework for collaboration (Oraee et al., 2017); a unified and more mature BIM competency framework (Succar, Sher, & Williams, 2013); frameworks that drive investment in data production and publishing (Abella et al., 2017); and frameworks for understanding stakeholder needs (Bosher et al., 2016). Of course, the best way to learn from any of these initiatives is an evaluative framework that outlines both qualitative and quantitative KPIs, as recommended by, for example, Caird & Hallett, (2018)

Theoretical frameworks for digital built Britain were relatively rare, but notably Mora, Deakin, & Reid (2019) explore competing mental models in research that need to be resolved. In their view, the proliferation of 'subjective, personal and isolated interpretations' of smart built environments has led to divergent paths in the literature, making it difficult for researchers, decision-makers and practitioners to progress. Multiple dichotomies have grown up in tension with each other, which, if left unresolved, will continue to limit progress in research and practice. These are:

- Whether smart cities should be led by technology or developed holistically as socio-technical systems
- Whether they should develop top-down, by government or market mandate, or bottom-up, by listening to and meaningfully engaging with the public
- Whether development should be driven by collaboration between market and government alone, or whether more stakeholders should be involved
- Whether initiatives should focus on a single dimension (e.g. smart cities as a climate change solution) or multiple integrated dimensions (e.g. climate, social wellbeing and justice, economic stability and safety performance of built assets)

Each of these options has strengths and weaknesses; and introduces questions that must be asked and tradeoffs that must be made knowingly.

Similarly, Meijer & Bolívar (2016) uncovered three different ideological definitions of smart cities in a review of the literature: 'smart cities as cities using smart technologies (technological focus), smart cities as cities with smart people (human resource focus) and smart cities as cities with smart collaboration (governance focus).' According to their findings, technology had the greatest concentration of any single type, followed by governance and then human resources. This demonstrates the dominance to this point of the technological narrative of digital built Britain, to the exclusion of research that defines its outcomes and impacts on human lives and the natural environment.

Categorising smart cities and smart built environments is not a purely theoretical effort. The mental models decision-makers work with frame the problems and in part determine the solutions. For example, 'if policy-makers want the natural environment not to lose ground... or even to incur gains..., some city categories may be more suitable than others.' (de Jong et al., 2015) At present, the literature is split between different competing concepts of smart built environments (e.g. Meijer & Bolívar, 2016), but working toward a functional consensus in this area guided by a joint framework could help break down existing siloes.

Decision-making

A common theme in the gap analysis is decision-making, particularly how decision-making about the built environment is being transformed by big data analytics. For example, according to Akter et al. (2019), 'Studies on [big data analytics (BDA)] are still only nascent and BDA-based decision-making and problem-solving to the most part remain unexplored, requiring thereby further investigation.' Indeed, numerous authors point to it as an area that needs further work, and it is one of the most prevalent examples of a topic that breaks across siloes in the literature (see **FIGURE 1**).

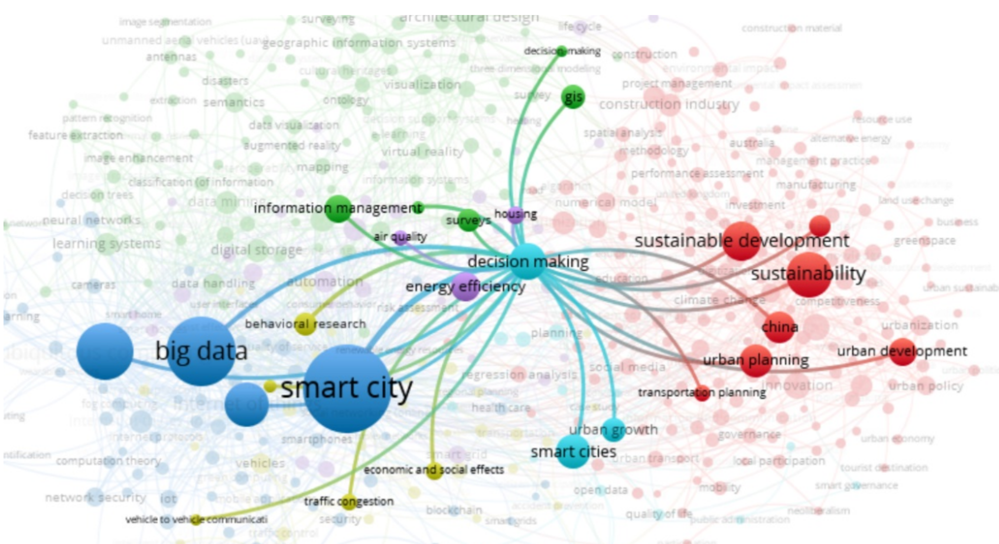

Figure 1 - Keyword co-occurrence (top 2,000 most cited papers in 2019 from the Search 8 results. See Appendix 1 and 2.)

Akter et al. (2019) outline a framework of the six steps of analytics-based decision-making, which itself could prove a useful basis for a unified digital built Britain decision- and evaluation-support framework. Meanwhile, research is needed to ensure that interactive visualizations of data as decision-tools are designed in ways that communicate uncertainty and communicate trade-offs clearly. (Grêt-Regamey et al., 2013)

Built environment

Many of the authors point to mature, or at least very active, research communities for the built environment. Refurbishment and legacy assets are key issues identified by e.g. He et al. (2017), while Liu, Deng, & Demian (2018) and others point to the need for more mature understanding of site management, structural health monitoring, O&M, positioning and planning/design using sensors in the built environment. Several authors point to the need for BIM, Augmented Reality and other technologies for safety and performance of transportation infrastructure (e.g. Costin et al., 2018), as well as the need for integration with facilities management (e.g. Owen et al., 2013) According to (Matarneh et al., 2019), 'The future agenda in this area involves: (1) integrating different facility performance information sources to perform retrofit simulations for decision making, and (2) integrating mixed reality along with BIM to facilitate refurbishment decisions.'

Human and social outcomes

The siloed history of engineering and social research has led to a critical gap in the literature. Missing from the literature about technological solutions is an in-depth discussion and debate over what problems they solve, prioritizing technically specified performance over social needs. This gap is in part encouraged by the journals that publish BIM literature. These editors could play a role in encouraging more interdisciplinary research by encouraging and publishing more papers that address society's requirements from BIM. (Hosseini et al., 2018)

Similarly, social science research relevant to dbB tends to miss out the technical specificities of ICT and engineering, meaning that, 'the depth and breadth of implications that emerge at the intersection of innate social problems and ICT in urban space remain underexplored.' (Lytras & Visvizi, 2018) There is some doubt, for example, about the acceptability of specific ICT interventions in urban environments. In Lytras & Visvizi's (2018) research, a group of potential smart city service users 'express very serious concerns regarding the utility, safety, accessibility and efficiency of those services.' Getting the details right for the right locations, users and services, then, is interdisciplinary work requiring tighter integration of social science, engineering and computer science research.

Finally, Gurevich, Sacks, & Shrestha (2017) identify a role for research in identifying how BIM and other ICT implementation interacts with existing power structures, noting that, 'Critical social theory in public administration suggests that a technology like BIM is often adopted by organizations into existing systems in ways that promote entrenched interests rather than the interests of the citizens they ultimately serve.' Social research can identify how BIM and ICT adoption will progress, and identify how best to level the playing field so that existing power structures are not even more deeply entrenched as we move toward a digital built Britain that benefits all of society.

Interoperability

Though there is a large body of literature addressing and providing solutions to interoperability challenges, there is more work to be done to scale up, align and put these solutions into practice. (e.g. Andriamamonjy et al., 2019; Howell et al., 2017) According to Matarneh et al. (2019), 'Among many unresolved issues that need to be addressed for successful BIM implementation, information exchange and interoperability remain the main issues.' They go on to categorise the many varied technologies and solutions to the interoperability issue, noting that it is the most investigated area in the papers they consulted.

Research patterns

Bibliometrics were used to identify collaborative networks by comparing the affiliations and countries of origin of co-authors. This work reveals silos where there are 'few institutional cross-linkages' in the UK, Australia and Canada, and points to a 'lack of cross-fertilization of ideas' between institutions and nations. (Hosseini et al., 2018) Li et al. (2017) have identified 60 distinct areas of interest within the BIM literature and 10 research clusters, but Hosseini et al. (2018) warn that the clusters tend to be inward-facing and self-referential rather than expansive and inclusive of multiple disciplines. These analyses point to silos of institutional affiliation and area of interest as well as those of discipline explored above.

An analysis of papers and citations by category conducted by Santos, Costa, & Grilo (2017) found that, 'even though Collaborative Environments and Interoperability is the category with the most papers published, it was the BIM adoption and standardisation category that had the most cited articles (28%).' This indicates that the topics that are of interest may not be the ones receiving the most intensive research effort. However, there are many different reasons for citation and publication rates that have little to do with the topic, and so the usual caveats about bibliometrics should apply.

Directions for further research

Despite commonalities among the gaps identified by the authors included in this review, there is far more variation in the recommendations for further research. Many of the authors approach questions of 'what next' from a particular silo or agenda. Many agree, however, that there is insufficient empirical research in various areas. To this end, Mora, Deakin, Reid, & Angelidou (2019) developed a research method for large-scale multiple case study analysis. This method, if adopted by others, could lead to a greater body of comparable knowledge from smart city initiatives and enable us to extract more value from past investments. Even if others wish to expand or improve upon this research, this type of unifying and multidisciplinary thinking is important for building future capabilities. This research should happen in collaboration between academia and industry, so both can learn from each other's expertise. (Costin et al., 2018)

Where participatory methods are used, Afzalan, Sanchez, & Evans-Cowley (2017) caution that the tools used and the planning authority or researcher's attitude toward it, can influence the results, as can citizen attitudes, norms, and many other factors. Slowing down to plan the type of intervention based on these contextual factors can yield more valuable results than rushing in with the latest technology.

Conclusions

Because the gap analysis used a pre-existing framework, there were various preconceptions about where the gaps would be found. In large part these preconceptions were validated by the findings. However, there were several surprises. First, a larger than expected body of literature addressing the research gap in the area of value, frameworks and decision-making was identified. Second, fewer authors than expected had made the explicit connection between the built environment and the services it delivers, despite the large volume of work on smart cities. Finally, the results confirm that very few researchers are looking into the full scope of digital built Britain and bringing together previously siloed areas. This indicates that the capability framework is a potential tool for unifying these currently siloed disciplines under a new research agenda for digital built Britain that takes a more holistic approach to digitalization and decision-making about the built environment.

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Appendix 1 – Method

The scoping review for this report occurred after several months of work had already been done on the capability framework. This meant there were already preconceptions about the gaps that would be identified. The first step was an iterative search for bibliometric, scientometric and literature reviews (**APPENDIX 2**). Relevant details from the results were captured in a spreadsheet, along with the state of research according to the authors. These gaps were then sorted according to the capability framework, and labelled red, amber or green according to the criteria noted below. Roadmaps identified earlier in the capability framework research were added and analyzed along the same lines. The heatmap in the **REVIEW** section was produced by assigning an intensity of colour related to the relative number of documents that had identified each category with each colour, so that where there were the greatest number of articles identifying a gap in the literature, for example, the red is most saturated. This is based on a small sample size and subjective judgements, so is predominantly for illustrative purposes. Finally, the author looked for insights deriving from the individual papers assessed as well as the light-touch bibliometrics for the searches in this review.

Because authors' ways of describing a research landscape vary so widely, the process of sorting the research topics into red, amber and green was subjective, but there was an attempt at consistency. The language used could be unhelpful at times for RAG categorization, e.g. 'there is a growing number of papers on…' Therefore, interpretation of whether something would be red, amber or green was based on contextual clues from the paper. If a research gap was listed in the body of the text along with several sources, it was usually amber if no other clues were given, and if something was listed in a 'further research' summary at the end it was usually weighted more toward red if no other clues were given. Where an active body of research was described, but the work that community needed to do was considerable, it was weighted more toward amber rather than green to reflect that it does not offer fully mature and scaled up solutions.

This method also inherits the limitations of the papers it identified. Few of the papers attempted the enormous task of cataloguing and categorising an area as wide as digital built Britain. More often they focus on a facet of interest: e.g. e-governance and BIM; BIM in engineering curricula; ontologies for BIM; social theories of smart cities. As a result, the gap analysis table in **Appendix 4** reflects the predilections and opinions of the authors of the papers included. Many of these reviews did present a more well-rounded approach than the table implies, but may have categorized research topics without indicating the volume or maturity of research in those areas, meaning that no RAG categorization was possible.

One further caveat about the method must be mentioned: the majority of cells in the gap analysis are blank, or are amber. However, blank cells do not indicate that those categories are unimportant, nor that there is necessarily a gap in the research, just that the paper did not mention them. Lower numbers in categories such as 'services' may indicate that the search terms did not bring back complete results, not that there is a gap in the literature. This is remedied by most authors also performing a critical review of the papers they found. However, authors may have left well-trodden areas out, and focused where there is enough of a research community to justify further research funding. True research gaps (areas where there is no ongoing work), and areas that already have a strong foundation of research may be less well represented by this method, evidenced by the relative paucity of red and green cells in the gap analysis.

While there are numerous caveats about this process, the author is confident that these results are indicative and useful for informing the digital built Britain capability framework. When applied to the Capability Framework, the reviews echo insights received through CDBB workshops, consultations with experts and the research networks. They also help stitch together a broader picture of where research is underway but is not as mature, aligned or integrated as needed. A great deal more work should be done to delve into the detail of exactly which research questions need to be answered, and to prioritise this research.

Appendix 2 - Search strategy development

Given time restraints, the search strategy used was iterative, gathering relevant sources at each stage, rather than strategic and exhaustive. As such, there are certainly limitations and gaps to this approach. First, only one database was used. From previous searches it was clear that this database has the highest volume of relevant results in this research area, but there may be articles missing from this approach that may have appeared on another database. Second, there are relevant topics that may be missing from this search. An exhaustive list of synonyms was not produced, but the most common terms from previous searches were employed, with the aim of balancing efficiency and completeness. Third, identifying relevant articles was done by title and abstract. The author has no academic background in this topic so the selection process may have been flawed. Several subjective decisions were made at this stage, e.g. as to whether a paper was too specific to be useful to the broad scope of this review.

While there are numerous caveats about this process, the author is confident that these results are indicative and useful for informing the digital built Britain capability framework. The searches used and how the results were used follows below.

Search 1

> *Scopus 09/05/19: TITLE-ABS-KEY ((bim OR "building information modelling") AND (bibliometric* OR scientometric*)) 2015-2019 = 25*

This search had the highest degree of relevant results. The BIM literature is already branching out and embracing the potential in the operation, management and integration space, meaning it is highly relevant to the agenda for digital built Britain and is beginning to scope the research capabilities that will be needed in the future. As such, 16 of the 25 results were added to the gap analysis. However, the focus of these reviews tends to be either on narrow facets of the research, or on creating competing taxonomies for BIM topics and research areas.

Search 2

> *Scopus 13/05/19: TITLE-ABS-KEY ((bim OR "building information modelling") AND (literature AND review)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") = 318*

The results of this search were too specific and generally off-topic to be informative to this study. Furthermore, literature reviews tended to use the literature to shape an argument, rather than discuss the size or maturity of the various bodies of research. While several documents were consulted, only three contributed to the gap analysis. The keywords 'literature AND review' were not used again based on these results.

Search 3

*Scopus 13/05/19: TITLE-ABS-KEY (("digital transformation" OR digit*ation) AND ("built environment" OR buildings) AND (bibliometric* OR scientometric*)) = 1*

This article could not be accessed from Cambridge and therefore it was not included. However, removing the keywords '"built environment" OR buildings' led to too many irrelevant results and so this was a dead end in the search process.

Search 4

*Scopus 13/05/19: TITLE-ABS-KEY (("digital transformation" OR digit*ation) AND (bibliometric* OR scientometric*)) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015)) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar")) = 11*

As with the previous search, '"digital transformation" OR digit*ation' was too generic, so that the results retrieved were not relevant to the capability agenda. No results from this search were used.

Search 5

Scopus 13/05/19: TITLE-ABS-KEY (("smart cit") AND (bibliometric* OR scientometric*)) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015)) = 27*

The results of this search were much more relevant. Although the scope of digital built Britain is bigger than individual cities, it is at this scale that issues are currently playing out at the intersections of data, governance, value and the built environment. Smart city research will be incredibly informative to decision-makers and researchers wanting to work toward a digital built Britain. That being said, only three articles of the 27 were considered to be relevant and broad enough to provide insights for the gap analysis.

At this point there was an attempt to cast a wider net and gather some bibliometrics related to an inclusive search for as much dbB-related research as possible.

Search 5

Scopus 14/05/19: TITLE-ABS-KEY (("smart cit") OR (digit*ation AND (buil* OR aec*)) OR ("digital twin") OR ("common data environment" AND (buil* OR aec)) OR (bim OR "building information m*")) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar")) = 28,808*

This search resulted in huge numbers of false positives from biology, medicine and physics, so the search was refined.

Search 6

> Scopus 14/05/19: TITLE-ABS-KEY (("smart cit*") OR (digit*ation AND (buil* OR aec*)) OR ("digital twin") OR ("common data environment" AND (buil* OR aec)) OR (bim OR "building information m*")) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar")) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "VETE") OR EXCLUDE (SUBJAREA , "DENT") OR EXCLUDE (SUBJAREA , "NURS")) = 23,557

This search seemed promising and an initial set of bibliometrics visualisations were gathered (see **Appendix 3**). However, on reflection other topics related to digital built Britain might have been missing, such as smart operations, services, e-governance and smart contracts. The search was refined again.

Search 7

> *Scopus 14/05/19: ("smart cit*") OR (digit*ation AND (buil* OR AEC*)) OR ("digital twin") OR ("common data environment" AND (buil* OR AEC)) OR (BIM OR "building information m*") OR ("smart operations" OR "smart facilit* management") OR ("digitally enabled services" OR ("integrated services" AND digital)) OR (digital AND design AND build AND operate AND integrate) = 110,725*

This large set of results needed to be filtered to exclude false positives as before and to narrow it down to the document types that were most likely to be helpful.

Search 8

> *Scopus 15/05/19: ("smart cit*") OR (digit*ation AND (buil* OR aec*)) OR ("digital twin") OR ("common data environment" AND (buil* OR aec)) OR (bim OR "building information m*") OR ("smart operations" OR "smart facilit* management") OR ("digitally enabled services" OR ("integrated services" AND digital)) OR (digital AND design AND build AND operate AND integrate) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "DENT") OR EXCLUDE (SUBJAREA*

, "VETE")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "bk")) = 57,719

Another set of bibliometrics graphics were gathered for this query, shown in Appendix 2.

Search 9

Scopus 15/05/19: ("smart cit") OR (digit*ation AND (buil* OR aec*)) OR (bim OR "building information m*") OR ("smart operations" OR "smart facilit* management") OR ("digitally enabled services" OR ("integrated services" AND digital)) OR (digital AND design AND build AND operate AND integrate) AND (value AND outcomes) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "MEDI") OR EXCLUDE (SUBJAREA , "MATH") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "AGRI") OR EXCLUDE (SUBJAREA , "CENG") OR EXCLUDE (SUBJAREA , "HEAL") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "DENT") OR EXCLUDE (SUBJAREA , "VETE")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "bk")) = 1,835*

True bibliometric analyses take time, as well as specialist skills and software. Therefore, the bibliometric approach was abandoned and once again the results were browsed for resources that would contribute to the gap analysis. They were sorted by number of citations and skimmed for relevant titles, down to papers with 1 citation each. A number of tabs were opened during this process. Then these results were filtered for the keyword 'review' and those with a UK affiliation. This filtering brought the number of results down to 195. The abstracts of all of these were skimmed for relevant papers, which were then read and added to the gap analysis. The logic behind limiting it to UK affiliations was that the focus of the research landscape is on the UK's research capability, and while there is useful and relevant research happening abroad, this was another chance to feature research happening in the UK.

Search 10

*Scopus 21/05/19: (TITLE-ABS-KEY ("natural environment" AND "built environment") AND TITLE-ABS-KEY (model*ing)) = 24*

A gap in the overall picture emerged after beginning to conduct the gap analysis and it was clear that the natural environment was largely missing from the picture. Smart cities were discussed as responses to climate change in the broad, contextual sense, and drives sustainable construction, but this was not discussed as an in-depth relationship. Indeed, sustainability is such a popular buzzword that it would be likely to bring up too many false positives. Instead, "natural environment" was used. Some of the results were irrelevant, as they merely happened to mention, e.g. large windows used to bring a sense of the natural environment into a building.

Search 11

*Scopus 21/05/19: (TITLE-ABS-KEY ("ecosystem services" AND "built environment") AND TITLE-ABS-KEY (model*ing)) = 5*

Although none of the results of this search were relevant, it prompted a citation chain that yielded two useful results.

Search 12

Scopus 21/05/19: TITLE-ABS-KEY ("social outcomes" AND (bim OR "building information m")) = 0*

Another under-discussed piece was social outcomes, but this keyword returned no results for either BIM or "built environment". This either means that other keywords are used or this is not a well-researched area.

Search 13

Scopus 21/05/19: (TITLE-ABS-KEY (social AND ("smart cit")) AND TITLE-ABS-KEY (review)) = 185*

This search revealed that "social inclusion" and "social capital" are more prevalent terms, as are "citizen centric" and "accessible". The smart cities research tended to have more to do with e-governance and processes than the built environment or services.

Search 14

Scopus 21/05/19: (TITLE-ABS-KEY ((social AND (inclusion OR capital)) OR accessibility) AND TITLE-ABS-KEY (review) AND TITLE-ABS-KEY (bim OR "building information m")) = 10*

None of the results were relevant to broader social outcomes. One dealt with social factors as a driver for BIM, and several others discussed physical accessibility to assets during construction or operation.

Search 15

Scopus 14/05/19: TITLE-ABS-KEY (("digital economy" OR "digital society") AND (bibliometric OR scientometric*)) = 3*

Only one result from this search was relevant and was added to the gap analysis.

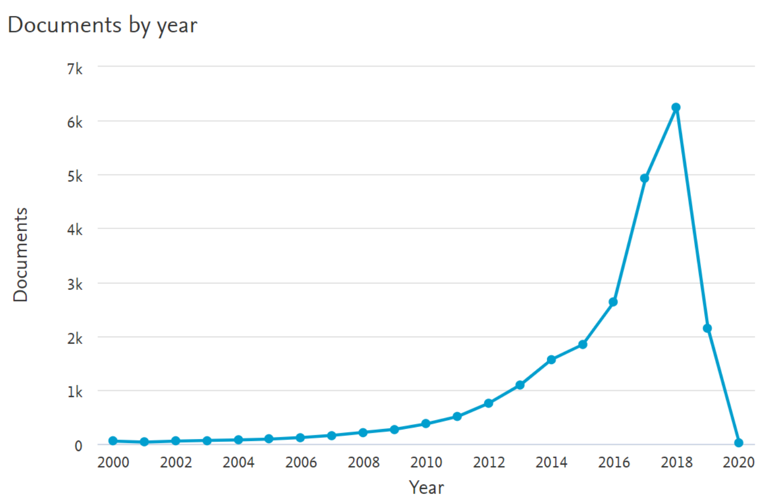
Appendix 3 – Bibliometrics

Bibliometric analysis, or the measurement and study of bodies of literature, is a growing method for analyzing research landscapes and gaps. However, it is important to not take the statistics at face value. Bibliometric methods can describe the quantity written about particular topics and how the patterns of publishing, citation and keywords break down, but even the best literature searches are reliant on the quality of the bibliographic data provided and critical thinking is still needed to identify the gaps and find meaning in the bibliometrics. Not all bibliographic analyses are equally authoritative, so although this paper does not assess the quality of the reviews identified, it is important to take bibliometrics with a dose of critical thinking.

The bibliometric analysis producing the graphics below is done automatically by Scopus and is very simplistic. However, it can provide limited insight into trends in publishing in particular fields.

Search 6

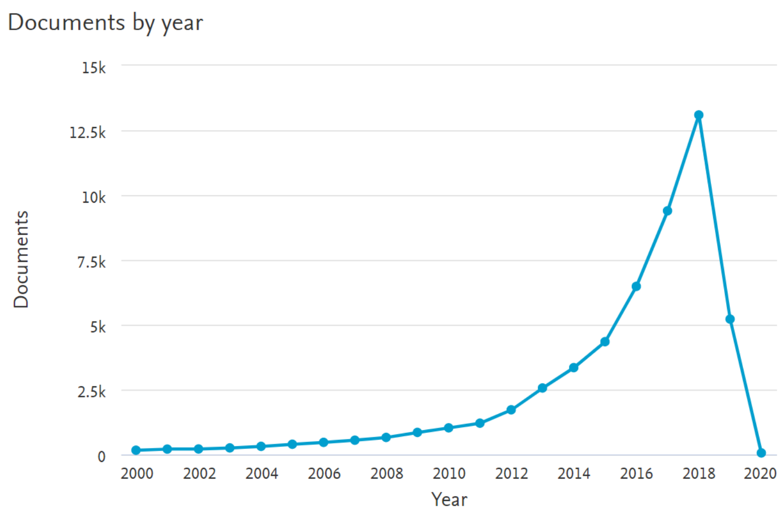
(See **Appendix 2** for the query that produced these results.)



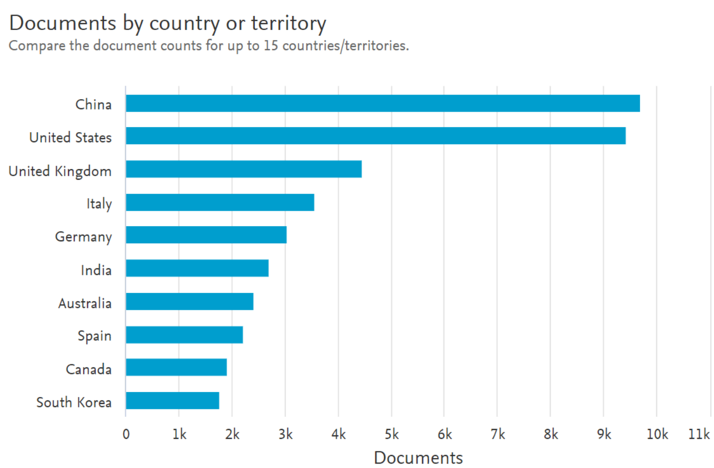
This narrower search produced similar results in terms of a growing body of literature since 2000, spiking rapidly since 2016.

Search 8

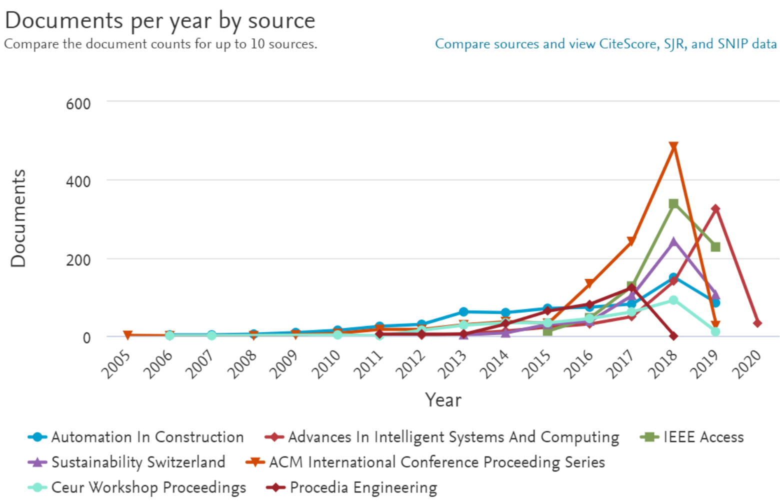
Search 8 involved the largest set of keywords in this process, and casting a wide net (while trying to minimize false positives) delivers a huge number of results. The graphics below generated by Scopus indicate the size and distribution of the digital built Britain research agenda.



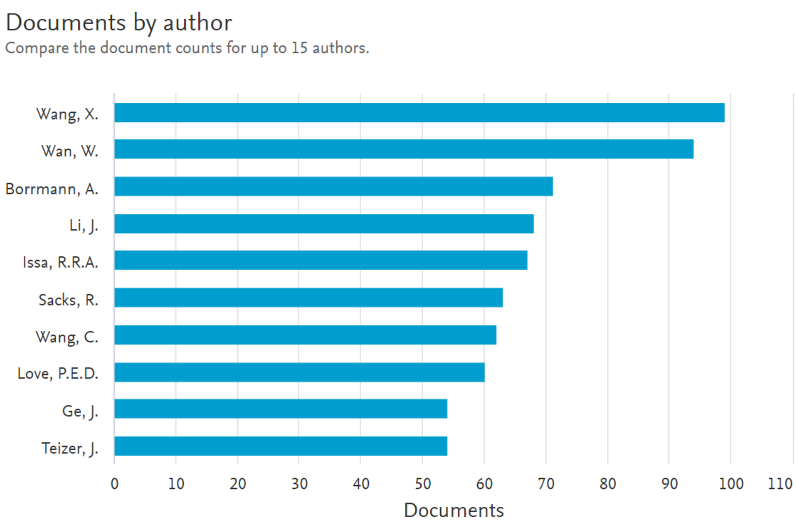
Looking at the number of documents published per year, we see a steady increase since the year 2000, peaking in 2018 with 13,094 publications. At just under halfway through the year, 2019 looks on track to equal that number.



Over this same 20 year span, authors affiliated with China have been the most prolific in this area, followed closely by the United States. Authors from the UK come in a more distant third, with just under 4.5 thousand documents in this area.

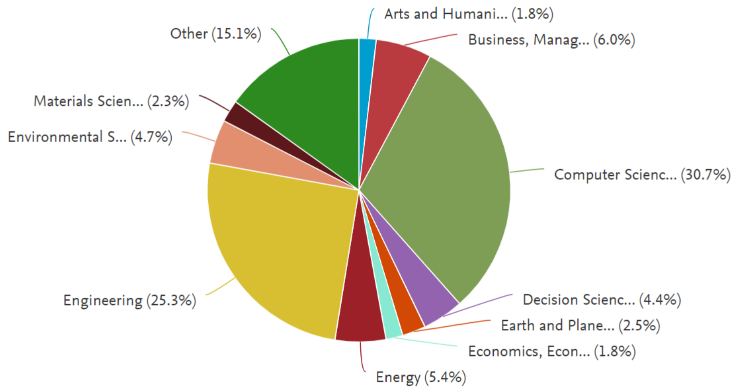


Among the most active journals and sources in this field over the last 15 years are technical and sustainability focused journals, while social science focused journals appear less.



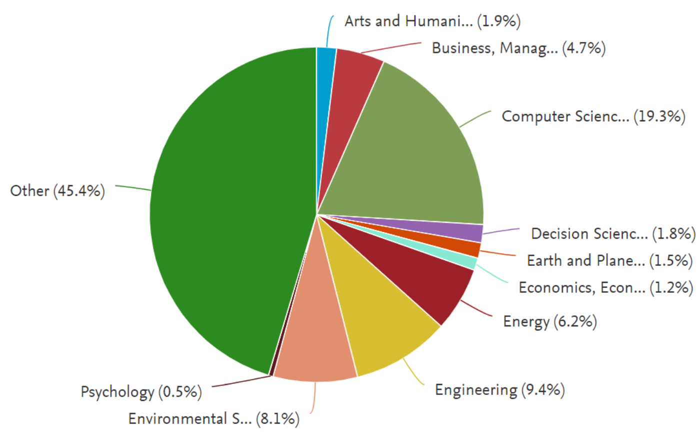
The most active authors during this period are shown above. As many of these authors were identified in an earlier unpublished BIM-focused review for CDBB, the identified body of literature seems to have a strong alignment with BIM research.

Documents by subject area



Over the last 15 years, the majority of the papers in this area were categorized as Engineering and Computer Science at a combined 56% of the total body of literature. However, in recent years this seems to be changing.

Documents by subject area



Looking at the 1,288 documents produced in 2019 so far, a greater percentage are classified as 'Other', a diverse category including social science topics and others. This may be an artefact of Scopus not yet having classification data on a greater percentage of papers, or it could point to growing interest in smart cities and other digital built Britain-related issues from other disciplines.

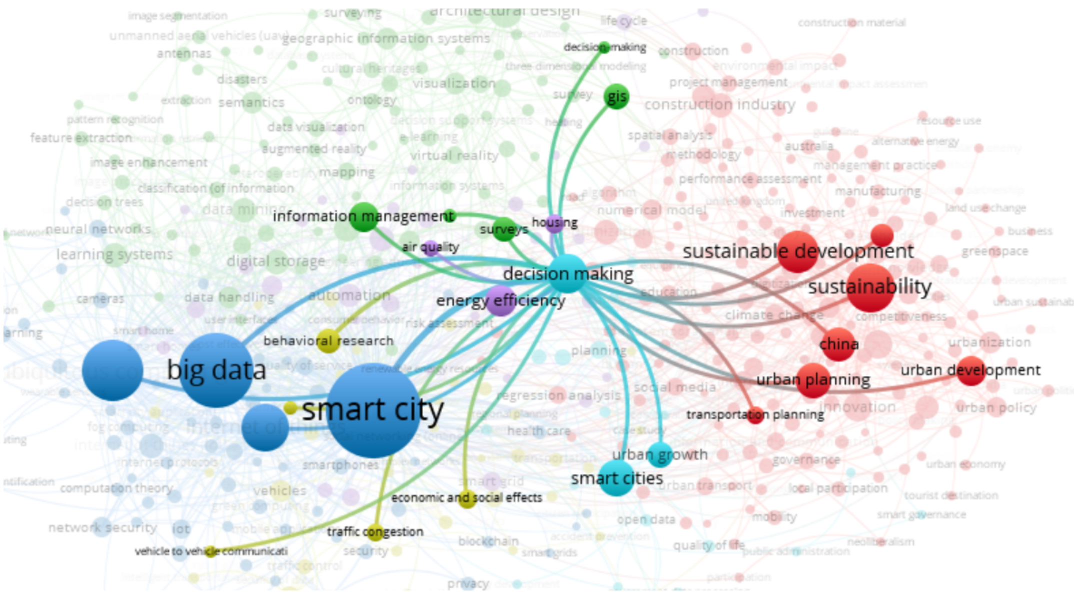


Figure 2 - Keyword co-occurrence (top 2,000 most cited papers in 2019 from the Search 8 results. See Appendix 1.)

Keyword co-occurrence (top 2,000 most cited papers in 2019 so far from the Search 8 results): This network of keywords most often used together shows the centrality of 'decision making' as a silo-breaking topic. Decision-making was a common recurring theme in the scoping review and gap analysis, and here we see that it is discussed throughout the different keyword clusters, though with less frequency than major keywords like 'smart city', 'big data' and 'sustainability'. This data was plotted and the graphic generated by using VosViewer, a piece of open source bibliometrics software.

Appendix 4 – Gap analysis

From bibliometric, scientometric and literature reviews published 2014-2019

Authors point to a major gap in the literature, maturity or capability.

Authors point to gaps that may have some initial work underway, or where the size and maturity of the research community were not indicated.

Authors point to a large body of literature or a very active research community. However, more research may still be needed.

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Abella, Ortiz-de-Urbina-Criado, & De-Pablos-Heredero, 2017	Creating a framework that drives investments in data production, publishing and promotions to capture value from big data Understanding what the public values and what creates value for the public (Social ROI)		Innovative business models based on big data, assess their impact		Decide dimensions for evaluating, e.g. security, privacy, ethics, and quality	Scale up and create demonstrators of existing models for deriving value from data	
Ahmed & Kassem, 2018						Investigate drivers of and barriers to adoption	
Airaksinen et al., 2016 [This roadmap presented barriers rather than research gaps]	Long-term investment vs. short term costs; doubts about ROI; lack of stakeholder input opportunities; city decision making in silos	Outdated renovation governance; Data monitoring vs services vs privacy is not clear regulated		Short term planning; building stock inertia; lack of ROI for environmental protection		Pilot already-developed solutions as demonstrators; incremental adaptation; assessing longer term impacts	
Akter et al., 2019	Understanding barriers to capturing value from big data analytics; processes and tools for integrating big data with decision making		Further research on big data analytics for service systems		A high volume of active research on technical processes surrounding big data	Developing organisational culture of decision-making based on big data analytics, and the local processes and know-how to achieve it	

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Alreshidi, Mourshed, & Rezgui, 2018		Collaborative governance; liability for 'bad' data, metadata, documentation; cloud-BIM governance requirements			Cloud-based BIM	Human barriers to change; technical skills	
Andriamamonjy, Saelens, & Klein, 2019	Demonstrating BIM benefits and adoption (active research community)		Poor integration of BIM in operational phase	As-built and construction monitoring (very active research community but more work to do)	Poor interoperability in practice	Achieving sector-wide BIM adoption Demonstrators/proof of BIM benefits to drive adoption	
Arup & UCL, 2017	Recognising the value of variety of input and opinion as insurance against vulnerability (strategic resilience); realising long-term value > short term efficiency			Understanding how and when to intervene in digitally connected infrastructure systems to improve resilience; infrastructure as complex adaptive system	Model vulnerability and resilience of built environment		
Ballew & Omoto, 2018				A large body of literature pointing to the psychological benefits of interacting with the natural environment on human psychology.			
Batista, Davis-Poynter, Ng, & Maull, 2017	Demonstrators and models of investability of trust and value-driven relationships between collaborators		Understand the tensions between collaboration and competition in servitization through outcome-based contracts				
Becerik-Gerber et al., 2014	Understanding the impact of built environment and context challenges to economic and social value			Infrastructure resilience to disasters; poor and degrading infrastructure; construction site safety	The ability of data sensing and analysis to meet these built environment and context challenges		Crude estimation of sea level; soil and coastal erosion; water quality; depleting groundwater; traffic congestion

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Bosher et al., 2016	Develop frameworks for understanding priorities in cities/communities, the role of stakeholders/actors and ways of collaborating			Develop new technologies and/or improve the existing technologies for reducing disaster risks and enhancing safe construction			Compile database of potential hazards and vulnerabilities, good practice
Caird & Hallett, 2019	Understand competing definitions of value through stakeholder and citizen participation Develop and implement indicator frameworks to measure development and performance outcomes				Better data and models for evaluating the outcomes and impact smart city initiatives		
Cerè, Rezgui, & Zhao, 2017		Empirically tested standardised metrics of resilience		Understanding the impact of geo-environmental hazards on building serviceability Large body of literature on theoretical and quantitative research on resilience	Risk modelling for building management systems		Understanding potential geo-environmental hazards
Cervero, Denman, & Jin, 2019	Applying empirical research about how people use existing infrastructure; understanding intangible drivers, e.g. cycling culture			Designing cycling infrastructure that considers human behaviour, natural environment resources and barriers			
Charef, Alaka, & Emmitt, 2018				End-of-life BIM			
Charef, Emmitt, Alaka, & Fouchal, 2019		Implementation gap: standardisation and sharing practice				Implementation gap: standardisation and sharing practice	

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Chong & Wang, 2016		A large body of BIM standards addressing sustainability practices in some stages of building lifecycle, especially front-end		BIM for optimization of resource use; alignment of BIM with green assessment criteria; BIM for renewable energy	Models to simulate the effects of climate change scenarios on the built environment	Implementing and adopting sustainable practices	
Clements-Croome, 2016	Understanding and controling the effects of rapid urbanization Understanding effects of urban environment on wellbeing; understanding how those investing in smart cities capture value while benefiting society	Ensure transparency around data and information; balance trade-offs between the natural environment and users of the built environment	Integrate water, energy service development	Design digital tools that enhance wellbeing in the built environment		Developing technology-aware workplaces; developing interdisciplinary collaboration	
Corsini, Certomà, Dyer, & Frey, 2019	Public participatory research			Developing the built environment in ways that benefit the natural environment			Smart cities as climate change solutions
Cruz, Rode, & McQuarrie, 2019	Assess and decide the right scale for case studies to solve difficult problems – city-level may not be the one	Analysing studies of smart city governance in light of heterogenous contexts and high context dependency Large body of literature on citizen participation in smart city governance			Develop literature on data that also considers governance		Better understanding needed of relationship between governance and context
Dainty, Leiringer, Fernie, & Harty, 2017	Understanding who benefits from policy interventions; how to avoid a two-tier market					SME perspective on BIM readiness; barriers for SMEs	
de Jong, Joss, Schraven, Zhan, & Weijnen, 2015	Livability; multifaceted outcomes; measuring social value			Investment in ICT infrastructure for information collection			Sustainable smart cities

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Fathy, Barnaghi, & Tafazolli, 2018					Process for IoT data management; discoverability tools; trust, quality, scalability etc. of data		
Ganbat, Chong, Liao, & Wu, 2018		How to conduct works across places with different BIM standards					
Grêt-Regamey, Celio, Klein, & Wissen Hayek, 2013	Interactive decision-making improves confidence, but many choices about the built environment are based on assumptions; understanding trade-offs				Methods for making urban ecosystem services evident as a trade-off for decision-makers		Identifying relevant ecosystem services to model
Gurevich, Sacks, & Shrestha, 2017	Understanding the different timescales of value for asset owners vs. occupants; tracing value back to investment in BIM			Post-occupancy evaluation of building performance with regard to occupant value (work by BRE)		Case studies using BIM Adoption Impact Map, for mapping relationships, impact of decisions and value of BIM adoption with regard to occupant value	
He, Wang, Luo, Shi, Xie & Meng, 2017	Managing stakeholder expectations	Policy transmission; contractual and legal interoperability		Existing buildings; operation & management; refurbishment; efficiency	Interoperability; real time visualisation	Evidence of successful adoption; collaboration	
Hosseini, Maghrebi, Akbarnezhad, Martek, & Arashpour, 2018	Social dimensions of BIM			BIM for infrastructure; integrating RFID and BIM		Learning from other disciplines/theories	
Howell, Rezgui, Hippolyte, Jayan, & Li, 2017	Large body of research on developing energy infrastructure to 'a centralized paradigm towards sustainability,		Active research community in smart metering; demand side management	Holonic energy distribution systems; system-of-systems optimization Understanding demand for energy supply points for electric vehicles	ML for smart distributed energy systems; semantic interoperability and security (active research		

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
	resilience and prosperity.'			Large body of literature on renewables, smart grid integration and distributed energy systems	communities, but a long way from solutions)		
Jin, Yuan, & Chen, 2019		Benchmarking sustainable construction practice		Application of recycled components in buildings; integrating new technology		Cultural change	Circular economy
Jin, Zou, Piroozfar, Wood, Yang, Yan & Han, 2019				VR and AI for safety management; worksite condition monitoring; hazard recognition	Taxonomy for safety monitoring	Safety culture; co-ordination and acceptance of safety frameworks and technologies	
Klein, Celio, & Grêt-Regamey, 2015	Case studies and examples of visualizing and communicating ecosystem services data for decision-making systems				Visualizing and communicating ecosystem services data for decision-making systems		
le Vine, Zolfaghari, & Polak, 2015	Analysis of whether automation makes people's lives easier/better	Policy requirements of automated vehicle travel, e.g. safety, intersection capacity etc.					
Li, Wu, Shen, Wang, & Teng, 2017	Decision making				Software; standards; ontology (active research communities but with much work to align and integrate)		Sustainable construction
Mahdavinejad et al., 2018	Environmental monitoring, crime monitoring, and social health; decision-making				Management of IoT data characteristics; security; learning algorithms and their dependency on data quality		

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Matarneh, Danso-Amoako, Al-Bizri, Gaterell, & Matarneh, 2019	More real-world examples/demonstrators			Guidance for facility managers; feedback process	Semantic integration and interoperability	More real-world examples/demonstrators	
Meijer & Bolívar, 2016	'Assess the contribution of smart city governance to both economic growth and other public values.'	More research on government transformation: 'A stronger connection to the literature in public administration on transformations from (old) public administration to (new) public governance needs to be made.'					'Analyze the politics of smart city governance.'
Nielsen, Larsen, Fitzgerald, Woodcock, & Peleska, 2015	Humans in the system-of-systems; case studies and demonstrators	Defining 'systems-of-systems'			No best practice on simulating emergence of behaviour in systems-of-systems Theoretical basis for other aspects of systems-of-systems		
Mora, Deakin, & Reid, 2019	Smart cities as socio-technical systems; mental models; dichotomies to resolve			Developing the built environment in ways that benefit the natural environment			Smart cities as climate change solutions
Olawumi, Chan, & Wong, 2017		e-Tendering; project management		Energy efficiency; design; structural analysis	Technology: cloud BIM etc.	Blueprints for BIM adoption; education	Sustainable construction
Oraee, Hosseini, Papadonikolaki, Palliyaguru, & Arashpour, 2017		Legal frameworks for collaboration		Engagement tools onsite		Collaboration literature (social science)	

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Owen, Amor, Dickinson, Prins, & Kiviniemi, 2013	Industry/enterprise business process innovation			Developing human/building interfaces; grow facilities management capabilities	Improving human behaviour modelling		
Palos, Kiviniemi, & Kuusisto, 2014	Cost/benefit analysis; communication	Contracts and legal; delivery standards			Open standard product libraries; interoperability with existing processes and tools; COBie definitions	Training and support systems	
Reynolds, Rezgui, & Hippolyte, 2017		Understanding drivers of demand-side energy management, e.g. governance, tariffs		Active research in intelligent building controls	District level energy modelling, management and optimisation Optimization of Building Management Systems (lots of disagreement about how); predictive modelling of actual energy demand		
Santos, Costa, & Grilo, 2017				Laser scanning	GIS integration; Tool development; semantic BIM (active research communities but much work to align and integrate)	Teaching and training	
Sivarajah, Kamal, Irani, & Weerakkody, 2017	Building a body of literature on extracting value from big data analytics; understanding value of big data	Regulating ownership of data in collaborative big data environments			Huge body of literature on big data/analytics tools (but little application)	More in-depth case study research and long-term analysis	

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
Succar, Sher, & Williams, 2013						Adapt and expand existing BIM competency frameworks to support e-learning, training and professional development	
Tah, Oti, & Abanda, 2017				Natural environment as a factor of geography and therefore a factor in modelling geographic information and city information	Integration of BIM with CIM: various isolated demonstrators that it can be done, multiple competing approaches		
Trotta & Garengo, 2018				Industry 4.0 processes: lean manufacturing, etc.		Lack of critical theory to underpin practical concerns, e.g. skills, changing job markets, etc.	
Visnjic, Neely, Cennamo, & Visnjic, 2016	Understanding benefits and challenges related to risk in servitisation; lock-in as a driver of loss Outcome-based contracts as a driver of value creation Large body of literature on characteristics of value networks relative to value chains.		Understanding the opportunities to create value that are opened up by services that assets/products alone do not offer				
Wang, Pan, & Luo, 2019					GIS integration		
Whyte, 2016	Considering CAPEX and OPEX holistically; mapping impact of systems integration decisions; understanding			Infrastructure as a complex product system; interaction of infrastructure with the natural environment; understanding rates of replacement	Tools for modelling risk to and resilience of infrastructure; data verification tools		Circular economy

Source	Value	Governance	Services	Built Environment	Data and models	Learning and adaptation	Context
	complex interdependencies				Techniques and tools for systems integration (lots of work but little consensus)		
Whyte, Stasis, & Lindkvist, 2016	Understanding how project baselines are negotiated, managed and controlled across complex projects				Ensuring data validity throughout a dynamic process Configuration management requirements for big data and complex projects Systems integration	Human behaviour in configuration process; what big data means for change management; establishing theoretical links between configuration management and complex systems	
Yin, Liu, Chen, & Al-Hussein, 2019				Integrating BIM with other technologies, e.g. VR/AR	Big data analytics for BIM best practice		Sustainable construction
Zhao, 2017	Evidence of Return on Investment					Engineering education	
Zheng Linzi, Chen Ke, & Lu Weisheng, 2019						Need for more interdisciplinary research	
Zhong, Wu, Li, Sepasgozar, Luo & He, 2019					Ontology development (IFC, Cobie); automated compliance checking		

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Sources:

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