GIRI

Get It Right Initiative

Barriers to the adoption of future digital engineering technology

UCL

Executive Summary

This report is in response to a requested for a proposal from GIRI for a desk-based study to help categorise digital engineering technologies and the barriers to their adoption.

Digital engineering is the use of digital technologies to innovate a new engineering business model and provide new revenue streams and value-producing opportunities. This study is focused on how error reduction and productivity gains can result from the reduction of barriers to digital engineering.

Digital Engineering is likely to mix and combine a range of technologies such as autonomous, semi-autonomous and manual operations with cloud, sensor, big data and 3D printing technologies to open unforeseen possibilities and create new engineering products, services and ecosystems. The inter-relationships are complex, so this study has tried to classify barriers according to five broad digital engineering phase categories:

- Digital enabled design
- Digital enabled procurement
- Digital enabled manufacture / sub-assemblies
- Digital construction / smart sites
- Digital facilities management / digital twin

While there has been significant Government and industry investment in digital engineering innovation. There has been very limited emphasis on reducing digital engineering barriers through phased progression though basic, collaborative prototyping and demonstration (e.g. progressing through technology readiness levels). To reduce barriers, reduce the risk associated with successful commercialisation, and to reduce potential failure there is a significant need to address the way that we invest in digital engineering.

While literature has classified and qualified the barriers to implementing digital engineering technologies, few studies have quantified the impact. As a result, how these technologies have increased productivity and reduced error has remained relatively under explored. This review, which was undertaken according to a strict methodology, focused on barriers as a mediator to reducing error and increasing productivity. It was found that:

- The literature showed various digital engineering **ecosystem and market barriers**, although little on the impacts of barrier removal.
- Few studies showed how removing digital engineering **policy, regulation and legal barriers** would impact error and productivity. Research into integrated project delivery and shared responsibility for error (e.g. integrated project insurance) could provide some insight although were not reviewed as part of this study.
- The impact of removing digital engineering **organisation strategy, collaboration and process barriers, Economic and finance barriers** and **technical barriers** are known to have an impact on error and productivity, however the direct effect of reducing barriers to digital technology implementation is not known.
- Evidence shows that digital engineering **data barriers** constrain productivity improvement and cause errors, although no studies showed the gains that could be made by their removal. Advances in data trust development require consideration.
- The impact of digital engineering **cultural and management barriers** on error and productivity have infrequently been investigated and so further research is needed.

A future research workshop could be used to determine which digital engineering barriers are easiest to overcome, which have the greatest potential to increase productivity through the reduction of error and where investments in research should be made. Funding could be sort for GIRI and its members through Government and industry funding.

Introduction

This report is written by Grant Mills (UCL Bartlett School of Construction and Project Management) in consultation with Clifford Smith. It is in response to a request for a proposal from GIRI for a desk-based study to help scope the barriers to the adoption of future digital engineering technology.

Academic literature has provided evidence for a categorisation of digital engineering barriers that could inform future research into the impact of barrier reductions on productivity gains and error reduction.

During the course of the study it was agreed that the work would be competed in two phases. The principle questions in this phase one literature review were:

- What constitutes the most significant categories of digital engineering?
- What are the barriers to adopting these digital engineering categories?
- Which digital engineering barriers influence which parties? (e.g. clients. contractors, consultants and suppliers)
- What is the level of existing investment in digital engineering research, development and demonstration within the UK construction sector?
- What funding might be obtained for GIRI and its members in the short-medium term.

The finding of this report may be used to inform a follow up phase that will answer questions such as:

- Which digital engineering barriers are easiest to overcome?
- Which digital engineering categories, if more effectively adopted, will most positively increase productivity and reduce error?
- Where does investment need to be spent to overcome these digital engineering barriers?

Recommendations are made for a second research phase, that will investigate digital technology adoption within the GIRI membership. It will identify a small number of research areas that appear to be under-resourced and highlight future funding opportunities.

Digital Engineering

Digital engineering is the use of digital technologies to innovate a new engineering business model and provide new revenue streams and value-producing opportunities.

As such, it goes beyond the application of various digital technologies.

The five categories of digital engineering used in this study are:

- Digital enabled design
- Digital enabled procurement
- Digital enabled manufacture / sub-assemblies
- Digital construction / smart sites
- Digital facilities management / digital twin

These are further classified bellow and in Appendix 1.

There is variation in the extent of adoption of these digital engineering technologies across the industry, however there are some technologies such as BIM level 2 that have been more widely adopted (NBS Annual Survey). Figure 1 indicates the level of adoption, however further research is needed to quantify these implementation levels.

Category	Digital Engineering	Industry Implementation
Digitally Enabled Design e.g. BIM, BIM libraries, digital process and design management and VR		**Moderate**[1]
Digital Enabled Procurement e.g. Supply chain data analytics, blockchain and cloud computing, collaborative planning and integration		**Low**
Digitally Enabled Manufacture / Sub-assembly e.g. Modern Methods of Construction (MMC), lean and Industrialised manufacture and robotics		**Moderate**
Digital Construction / Smart Sites e.g. drones, computer numerical control, 3D printing, automation, augmented reality, digital skins		**Low**
Digital FM / Digital Twin e.g. sensors, BIM FM, locational GIS, remote sensing or internet of things innovation		**Low**

Figure 1. Five Categories of Digital Engineering

[1] 69% of the survey participants reported that they are aware and currently using BIM (NBS Annual Survey). Further details are provided in Appendix 1

Overcoming the Barriers to Digital Engineering

Critical to increasing productivity and reducing error is the implementation of new digital engineering technologies. However very little is known about the barriers that hamper and impede adoption. The figure below shows the need to better understand this causality to reduce digital engineering barriers as a means of increasing productivity and reducing error.

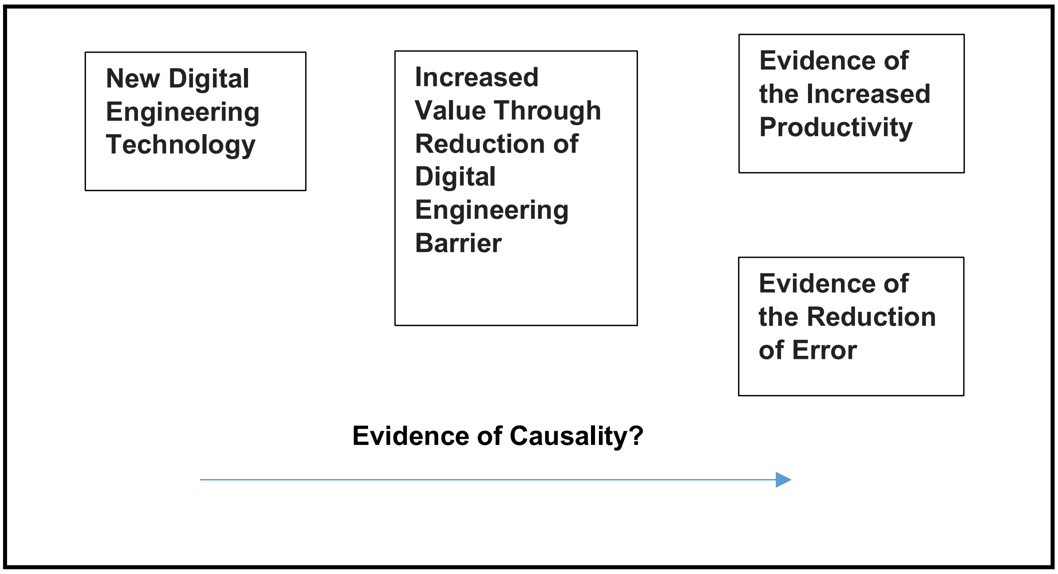

Figure 2. Reduction of Digital Engineering Barriers will Increase Productivity and Reduce Error.

Statistics show increased implementation of BIM over the last 10 years, increasing 13% to 69% (NBS Annual Survey). However, we do not directly know the impact of this on error reduction and increased productivity.

Many of us have worked on projects that have introduced a new technology such as BIM which has reduced productivity (due to learning new software or duplicating old and new methodologies). And on occasions these new digital technologies may lead to an increase in error (through missing a vital piece of data for example).

Research is needed to understand and measure how the industry can make incremental improvements in the implementation of new digital engineering technologies through the reduction of barriers that cause error or reduce productivity.

It is plausible that an increase in digital engineering will ultimately increase productivity and reduce error, but we need more evidence. We must find ways to measure the strength of association (relative risk, odds ratio) between digital engineering and productivity gain/error reduction. If we could see the direct size of the association (e.g. if you increase digital engineering you increase productivity and reduce error) we could better articulate the business case for adoption by repeatedly and consistently showing improvements across different studies and with different user populations.

The questions that future research might have to address are:

- In researching, developing and demonstrating new digital engineering technologies, how can management of technology readiness levels reduce barriers to productivity and reduce error?
- In increasing value through reducing these digital engineering barriers, what are the strategies such as alliancing, integrated project insurance and data trusts that might create a supportive environment to overcome barriers?
- How can we measure, collect evidence and visualise the impact of reducing barriers on error reduction and productivity gains?

Scope and Method

Two searches were undertaken using Google Scholar (since 2015), to understand the broad field of barriers to digital technology implementation.

These searches returned 3672 results (see appendix 2), titles and abstracts were reviewed of this long list of references, the refined to 70 references that warranted more detailed investigation. Once this was complete a snow-balling approach was used to select articles published before 2015 that warranted further investigation – 21 articles were reviewed (bringing the total to 91 references reviewed in full detail).

Central to the search was "barriers to innovation" in the use of “digital technologies” throughout the "construction supply chain". The search emphasised sources that were empirically grounded in case studies or systematic literature review and stratified across various digital enabling technologies according to those prioritised by GIRI. These included the barriers to supply chain innovation in:

- Digital, BIM, BIM library or BIM for FM
- Digital process optimisation and process improvement or efficiency
- Data analytics, common data, data environment, digital twin, AI, machine learning or big data
- Design optimisation or design management
- Construction process, construction method, MMC or modern method
- Lean construction or waste in construction
- Collaborative planning, collaboration or communication
- Modularisation, component standardisation, kit of parts or sub-assembly
- Offsite or onsite or manufacture
- Augmented reality, or virtual reality (VR)
- Optimising machinery, plant reduction or plant efficiency
- Drones, Computer Numerical Control (CNC), 3D printing or automation
- Sensors, remote sensing or internet of things
- GIS

This literature review provided evidence of the what constitutes the most significant categories of digital engineering and classified general and specific barriers to adoption.

Digital engineering and barrier categories are now used to quantify the level of digital engineering research, development and demonstration investment in the UK construction sector.

Investment in Digital Engineering

There has been various sources of investment in digital engineering, and significant targets set to directly increase productivity and reduce error. Recent Government and industry investments are quantifies below.

Government UK Research and Innovation Funding - Transforming Construction

Government funding has contributed to the implementation of digital engineering technology research, development and demonstration across the various Technology Readiness Levels (see TRL Figure 1 below[2]).

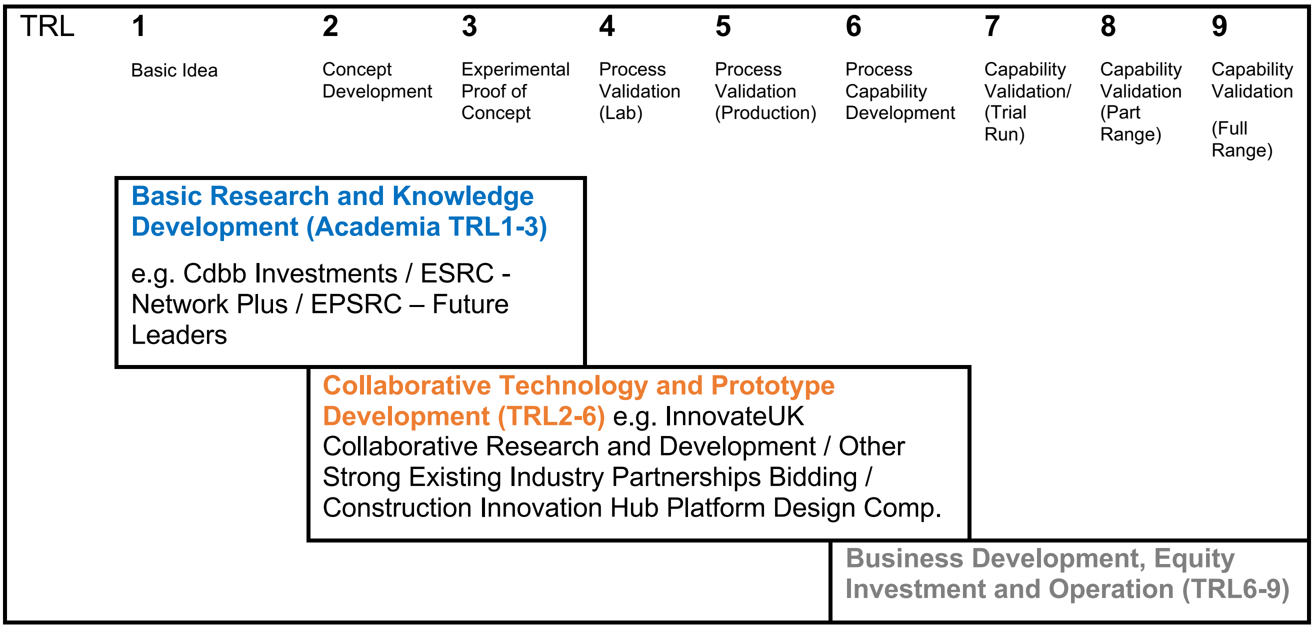

Figure 3. Technology Readiness Levels

There has been significant investment in both basic and development TRL phases across digital engineering categories. To enable digital design, procurement, manufacture, construction and facilities management (FM), the following investments have been made.

- **Digitally Enabled Design (~ £2.6m *Basic Research, and* ~ £2m *Prototype Development)*** e.g. BIM, BIM libraries, digital process and design management and VR
- **Digital Enabled Procurement (~ £2.9m *Basic Research,* ~ £0.9m *Prototype Development)*** e.g. Supply chain data analytics, block-chain and cloud computing, collaborative planning and integration
- **Digitally Enabled Manufacture / Sub-assembly (~ £0.4m *Basic Research and* ~ £72m *Prototype Development*** e.g. Modern Methods of Construction (MMC), lean and Industrialised manufacture and robotics
- **Digital Construction / Smart Sites (~ £4.3m** *Basic Research, and* **~ £3.8m** *Prototype Development)* e.g. drones, computer numerical control, 3D printing, automation, augmented reality, digital skins
- **Digital FM / Digital Twin (~ £0.9m *Basic Research and* ~ £0.2m Prototype Development**) e.g. sensors, BIM FM, locational GIS, remote sensing or internet of things innovation

[2] A more detailed description of the projects that have informed this figure is contained in Appendix 3

UK Industry Funding on R&D (e.g. internal investments made by client and their supply chain)

A recent survey performed by I3P showed that 46% of its membership had funded 282 digital engineering projects. The respondents included 6 client organisations and 9 contractors and consultants. Reports showed that these 15 organisations had funded circa £434m worth of research and development. The highest investment was made in digital construction / smart sites (49%), significant investment in digital FM (39%) and then 6% and 5% respectively for digital enabled design and digitally enabled manufacture. There was no reported investment in digital enabled procurement.

Combined Government and Industry R&D Funding

When combining Government and industry investment (Figure 4), this shows significant industry investment was made in digital construction and digital FM, while there is higher Government funding for collaborative technology and prototype development in digital manufacture. It is unclear how the spread and ratio of investment across these TRL levels has overcome digital engineering barriers to increase productivity and reduce error.

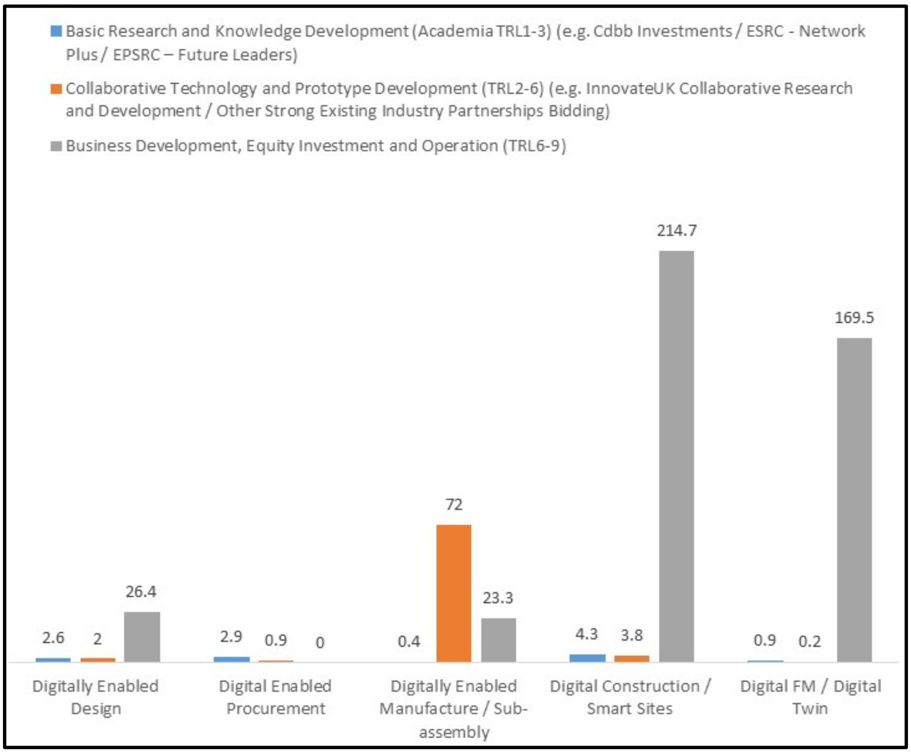

Figure 4. R&D Investment Across Technology Readiness Levels (TRL)

Reducing digital engineering barriers in design, procurement, manufacture, construction and facilities management requires utilising basic, collaborative prototyping and market demonstration. Progressing the maturity of a technology through these readiness levels reduces barriers and so it is critical that funding for innovation is managed industry wide. Basic research initiates technical capability development and facilitates the open source sharing of data, it helps to develop the market and policy response, to define the organisational and collaborative structures and align commercial and collaborative relationships and so it goes without saying that it can reduce barriers to digital engineering implementation.

As a novel digital engineering technology progresses through these basic, collaborative prototype and demonstration stages (from TRL1 to TRL9) the risk associated with successful commercialisation is reduced. The higher the TRL, the more it costs to achieve it and potential for failure. Reducing error and increasing productivity through the implementation of digital engineering must therefore address the assessment of industry maturity.

Barriers to Digital Technology Adoption

General Barriers to Digital Engineering

In general terms, barriers to digital engineering can be summarised as below:

- **Ecosystem and Market Barriers** e.g. Industry readiness, low customer acceptance, new professional capabilities, communication networks, lowest price procurement, industry relationships.
- **Policy, Regulation and Legal Barriers** e.g. GDPR, procurement, IP, required legislation, data security, duplication of policy development.
- **Organisational Innovation Strategy, Collaboration and Process Barriers** e.g. weak innovation processes, weak collaboration across the fragmented supply chain, trust and communication, lack of standardisation, restricted lowest price- tendering.
- **Economics and Finance Barriers** e.g. few tangible incentives, fast pace of projects, high investment, lack of available resources and ROI.
- **Technical Technology Barriers** e.g. technology research and scalability, different levels of maturity, lack of standards and standardisation, compatibility and infrastructure.
- **Data Barriers** e.g. Processing, storage, cleaning, ethical fears, negative perceptions.
- **Culture and Management Barriers** e.g. misunderstanding of digital, engagement and resistance, lack of focus on lean efficiency and productivity, customer-focus and top management commitment.

Each digital engineering barrier is now investigated to understand subtle differences, then research gaps are identified to focus attention on the evidence needed to reduce barriers that cause error or reduce productivity[3].

What is important to note is that most barriers are a function of a digital engineering categories maturity, for example technology and data will be high in basic research and diminish over time, ecosystem and market barriers grow in importance as digital engineering technologies get closer to market. As such, there is a complex interplay of barriers that vary over time and between digital engineering technologies.

Ecosystem and Market Barriers

Table 1 shows that the digital barriers in design and procurement involve who leads, who benefits and why firms should implement digital engineering. While, the digital barriers in construction and facilities management are associated with the cost of scaled implementation and lack of resources. Significant barriers exist as new digitally enabled manufacturing approaches are implemented. Appendix 2 provides further detail.

Table 1. Ecosystem and Market Barriers Across Digital Engineering Categories

Digitally Enabled Design e.g. BIM, BIM libraries, digital process and design management and VR	**Digital Enabled Procurement** e.g. Supply chain data analytics, block-chain and cloud computing, collaborative planning and integration	**Digitally Enabled Manufacture / Sub-assembly** e.g. Modern Methods of Construction (MMC), lean and Industrialised manufacture and robotics	**Digital Construction / Smart Sites** e.g. drones, computer numerical control, 3D printing, automation, augmented reality, digital skins	**Digital FM / Digital Twin** e.g. sensors, BIM FM, locational GIS, remote sensing or internet of things innovation
• Unclear benefits • Few incentives • Cannibalisation • IP and know-how • Brand image • Lack of leadership	• High competitive intensity • Lack of perceived need • Coordination • Scalability of data storage and speed	• Incentives • Government support for innovation • High initial capital cost • Traditional procurement and contracts • Adversarial relationships / trust	• Cost of technology • Low profit margins of the industry • Gaps in R&D investment • Shortage of technology-	• Variety of measures • Scale of application • Accessibility to commercial software • Open sourcing of code

[3] For a full description of existing barriers to digital technology implementation go to Appendix 2.

• Existing culture of claims • Design management	• Diversity of stakeholders and disciplines • Temporary and transaction project-based approach • Fragmented subcontractor model • Design barriers	• Lack of measure of quality and productivity losses • Market demand • Access to labour • Complex supply chain • Variability in projects • Lack of supplier involvement /weak collaborative planning • Capacity and attitudes	capable engineers • Security of data • Threat of artificial environment	

The impact of reducing ecosystem and market barriers on error and low productivity has not directly been measured, and so significant gaps exist. The impact of sharing IP, best practice and rewards in alliancing, and the impact of this on digital engineering (versus traditional design and procurement) could warrant study. As could the cost and resource constraints associated with scaling new digital construction and facilities management technologies and what the business case is for wider adoption. The complex interplay of barriers during manufacture warrant significant investigation.

Policy, Regulation and Legal Barriers

Table 2 shows that the digital barriers in this category are largely focused on who develops policy, who pays to inforce it and who takes responsibility. These digital engineering barriers to digital engineering appear to be relatively consistent across design, procurement, manufacturing, construction and facilities management phases, although there is likely to be variances dependent on the complexity of the project type and the nature of project-specific standards.

Table 2. Policy, Regulation and Legal Barriers Across Digital Engineering Categories

Digitally Enabled Design	Digital Enabled Procurement	Digitally Enabled Manufacture / Sub-assembly	Digital Construction / Smart Sites	Digital FM / Digital Twin
• Ethics and legal views of tracking and monitoring • Ownership and IP • Responsibility for errors • Taxation, • Lack of standards • Traditional procurement procedures	• Lack of contractual and legal precedence • Constraints of shared reputation • Confidentiality	• Low R&D budgets • Limited testing • Codes and standards • Innovation culture	• Cost and time of licensing drones • Robot-user interface restrictions	• Lack of clear regulation, standards and codes

Policy, regulation and legal barriers will impact error and result in low productivity. Within this review, there has been no literature sources that directly measure these impacts. They are likely to be significant sector differences, for example healthcare barriers to digital engineering may be more significant in complex infrastructure and healthcare sectors, than barriers to digital engineering in education or housing project sectors. The various institutional dynamics of these sectors and their approaches to insurance warrant further investigation. For example the impact of legal governance, integration project delivery and shared responsibility for error in integrated project insurance may impact adoption of digital engineering, could reduce error and drive greater productivity.

Organisational Innovation Strategy, Collaboration and Process Barriers

Table 3 shows that organisational innovation strategy, collaboration and process barriers are largely focused on who is involved, what is the structure, how are capabilities distributed and teams empowered in the process and how is alignment of commercial interests achieved. There appear to be consistent digital engineering barriers across design, procurement, manufacturing, construction and facilities management phases, with regards to organisational integration aspects.

Table 3. Organisational Innovation Strategy, Collaboration and Process Barriers Across Digital Engineering Categories

Digitally Enabled Design	Digital Enabled Procurement	Digitally Enabled Manufacture / Sub-assembly	Digital Construction / Smart Sites	Digital FM / Digital Twin
• Lack of planning • Length and inflexibility of supply chain • Lack of collaboration and integration • Process change • Innovation in supply chain partnership • Supply chain expertise • Leadership • Lack of shared risk	• Collaborative information sharing and data access • Trust, ethics, security • Competition • Principle-agent conflicts • Incentives • Leadership culture and capabilities	• Workforce • Fragmented subcontracting • Upskilling and training • Adversity to change • Communication • Innovation culture • Client, technology and site complexity • Lack of standard process	• Fragmented solution finding • Limited integration and learning • Weaknesses in data storage and processing • Technology generalisability and site scalability • Know-how sharing • incomplete construction planning • Weak coordination and quality control	• Ambiguity of requirements • Communication • Gaps • Errors • Fragmented planning • Workflows

The impact of organisational innovation strategy, collaboration and process barriers on error and productivity have not been directly measured. Although, approaches such as alliancing, which are known to facilitate the reduction of barriers to digital engineering (e.g. increase planning, supply chain integration, innovation, risk sharing, incentivise increase performance, data sharing, capacity building and standardisation) require further study.

Economics and Finance Barriers

Table 4 shows that the economic and finance digital engineering barriers are largely focused on making explicit the business models and resource requirements. Economic and finance issues are shown to impact on error and productivity throughout design, procurement, manufacture, construction and facilities management. Although, the relationship has not been evidenced.

Table 4. Economic and Finance Barriers Across Digital Engineering Categories

Digitally Enabled Design	Digital Enabled Procurement	Digitally Enabled Manufacture / Sub-assembly	Digital Construction / Smart Sites	Digital FM / Digital Twin
• High cost of equipment • Unclear benefits • Lack of business evaluation, • Complexity of the construction site-based environment • Access to capital • Financial risks • Overoptimistic demand forecasts	• Energy consumption • Exchange rates • Human error • Malicious attack • Timescale • Resource availability • Scaled capabilities • ROI • High software and licensing costs	• Cost to adopt robotics • High initial capital investment • Small scale of majority of companies • Few resources for product testing • Lowest price procurement • High training cost • Cost of advanced skills acquisition • Economies of scale	• Cost of technology • Cost of experimentation • Commercial time • Contestability pressures • Licencing problems • Short-term relationships	

The downstream implementation of digital engineering in manufacture and construction require investigation to understand the business case for scaled implementation. Barriers were seen to be exacerbated within small scale supply chain organisations. In addition, project-by-project procurement, competitive tendering and short-termism in pricing prohibited wide scale implementation of new digital engineering technologies.

Technical Technology Barriers

Table 5 shows the technical barriers that are largely centred on clear definition of process and product requirements. Technical barriers will almost certainly exist in the implementation of digital engineering in design, procurement, manufacture, construction and facilities management. Barriers in this category related specifically to the knowledge of opportunities and the capabilities to specify advanced requirements, and to manage innovation and technology maturity over the lifecycle of a business.

Table 5. Technical Barriers Across Digital Engineering Categories

Digitally Enabled Design	Digital Enabled Procurement	Digitally Enabled Manufacture / Sub-assembly	Digital Construction / Smart Sites	Digital FM / Digital Twin
• Lack of standards • Incompatibility • Reference architectures • Lack of SME capability • Technology management • Infrastructure	• Technology scope • Requirements • Scaling • Demand • Risk of tampering	• Unproven / immature technologies • Worker alongside robotics safety • High task complexity • Lack of standardisation • Separation of design and construction	• Robots-automation know-how • Lack of research, maturity of information management • Speed of manufacture • Diversity in batch size • Materials limits • Standardisation • Upskilling • Product libraries • Integrated technology processes	• Integration of BIM translation, transition and operation • Weaknesses in data maintenance

There is a need to investigate highly innovative digital engineering projects (which are somewhat error free and productive) and compare them to projects that lack project quality, or have a high cost of quality. The costs associated with barriers such as capability gaps, unproven / immature technology, error or lack of standardisation could then be calculated.

Data Barriers

Table 6 shows the need for shared data structures and standardisation. Barriers in this category relate specifically to the approaches taken to using data, although there was a lack of literature specific to the construction industry that showed the measurable impact of these barriers on error and a loss in productivity.

Table 6. Data Barriers Across Digital Engineering Categories

Digitally Enabled Design	Digital Enabled Procurement	Digitally Enabled Manufacture / Sub-assembly	Digital Construction / Smart Sites	Digital FM / Digital Twin
• Lack of information sharing • Developing a software architecture • Data sharing across supply chain • Knowledge management • Data security	• Data authentication • Stability • Capacity • Connectivity • Interoperability • Compatibility • Lock-in		• Required change in business • Reporting models within the industry • Privacy • National standards • Data structures • Legitimacy of usage context • Integration challenges	• Data quality • Interoperability • Automation

Because of the known capability gap in this area there is a need to develop skills to collect, clean, analyse and interpret existing data that might show the impact of known digital engineering barriers on error and productivity. There is also a need for research into the development of new trusted data architecture and reporting models that could provide evidence and overcome existing barriers to reduce error and increase productivity.

Culture and Management Barriers

Table 7 culture and management barriers are largely focused on why people are motivated and what capabilities they have. Research on the cultural and management barriers in the implementation of digital engineering in design, procurement and manufacture appears to be more mature than that in construction and facilities management.

Table 7. Culture and Management Barriers Across Digital Engineering Categories

Digitally Enabled Design	Digital Enabled Procurement	Digitally Enabled Manufacture / Sub-assembly	Digital Construction / Smart Sites	Digital FM / Digital Twin
• Deficiencies in supply chain management training and skills • Low technical competence • Fast and reliable connectivity • Resistance to change • Lack of awareness • Reputation • Usage • Coordination • Short-term view of ethics • Adversarial attitudes • Empowerment • Leadership	• Resistance to change • Skills • Fear of losing competitive advantage • Leadership • New roles • Use of real-time data • Lack of integration	• Aversion to change • Culture • Job security • Communication • Trust • Risk • Material and workflow planning • Integration and collaboration across fragmented subcontractors		• Training, expertise • Collaboration • Open information sharing

There is very little causal evidence that overcoming cultural and managerial barriers to digital engineering will increase productivity and reduce error, although this is intuitively known to be the case. Other fields exist that more explicitly show this causality (e.g. culture-productivity and culture-error), however these have not emphasised barriers as a mediating concept. There is perhaps a need to assess the awareness, attitudes and maturity of projects at both ends of the spectrum, to understand how their approach to digital engineering differs and what the impact is on the digitally enabled value chain.

Future Directions

Following the presentation of the draft report, the GIRI Technology Group met to discuss future directions (24 Sep 2019). The report showed the barriers to digital engineering adoption, but literature was by and large silent on how the removal of various barriers could increase productivity and reduce error.

The group were particularly interested in commissioning primary research that would build on previous work. The aim of this work would be to understand the variability in adoption barriers across the supply chain, and to quantify the impact of these barriers on productivity and error reduction. For example, this would ask the questions - how do barriers to adoption differ across client, design consultant, contractor and supply chain partners? And then what might be the impact of overcoming these barriers to specific organisations and to the overall value of the project? This work could then be used to benchmark and compare project supply chains and make recommendations on how the industry could create structures and align commercial incentives to increase productivity and remove error through barrier reduction.

It was agreed that the GIRI Technology Group would meet to prioritise which digital engineering barriers to research. For example BIM model coordination and integration was seen as a significant priority, which has the greatest potential (through increased investment) to increase productivity and reduce error. Once the scope of this research is identified, UCL would then devise a primary research methodology that would mix qualitative and quantitative methods to further specific the digital technology barrier, to qualify the severity of the barrier on productivity and error and the feasibility of its removal. Then to quantify the impact of reducing the barrier.

Various sources of Government funding, such as ESRC Network Plus, collaborative RCUK CR&D prototype development (such as those contained in Appendix 3), although it was agreed that a more focused approach should be taken that is directly responsive to problems posed by the GIRI membership.

Conclusions

This report has provided evidence of the most significant digital engineering categories and provided details on the known barriers to their implementation.

The report shows the level of existing government and industry investment in digital engineering research, development and demonstration with the UK construction sector.

Reducing digital engineering barriers in design, procurement, manufacture, construction and facilities management requires effectively utilising basic, collaborative prototyping and market research to reduce error and increase productivity. While the literature review has not been able to quantify this impact, but given that failure close to market might have been preventable (e.g through reduction of barriers at basic or collaborative prototyping level), it is foreseeable that the impacts of barrier reduction could be significant.

The report describes the various barriers (e.g. policy, market, economic, organisation, technical, data and culture) across the digital engineering phases (design, procurement, manufacture, construction or facilities management). It showed that while there is literature that has classified and qualified the barriers to implementing digital engineering technologies, there are few works that have quantitatively shown their impact on increased productivity and reduced error. This provides significant justification for future research.

A GIRI technology group workshop is needed to determine which digital engineering barriers are easiest to overcome and which have the greatest potential to increase productivity and reduce error. There is a shared interest to undertake further research to advance digital engineering through barrier reduction.

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Appendix 1 Current state of BIM use in the UK (NBS Annual Survey)

An annual survey conducted by NBS is carried out in order to examine the perceptions and trends associated with BIM use. 69% of the survey participants reported that they are aware and currently using BIM. Over the last 10 years, the uptake of BIM has increased from 13% to 69% (NBS Annual Survey).

An overview of the main barriers preventing organisations from adopting and using BIM is provided in the figure below. The most common barriers highlighted in the NBS Report (2019) include the lack of client demand (65%), lack of in-house expertise (63%), lack of training (59%), cost (51%) and no time to get up to speed (48%).

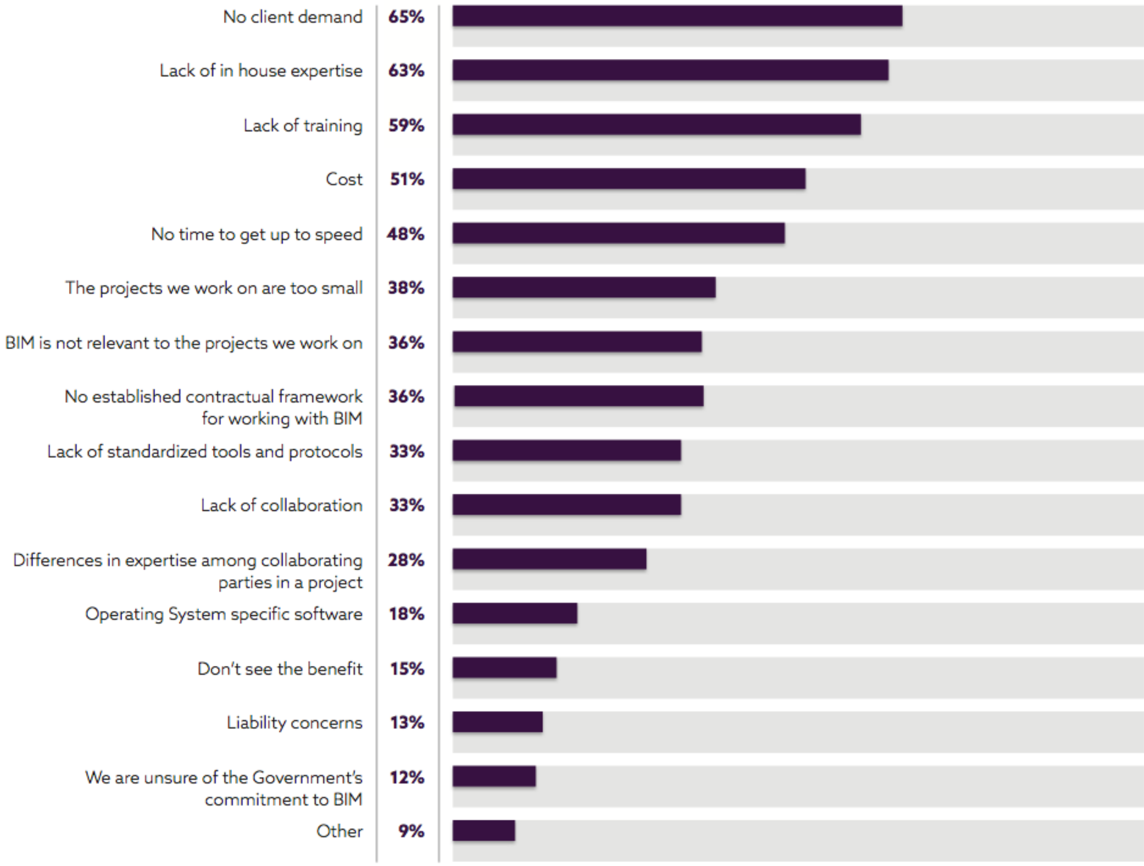

Figure: Main barriers to using BIM (Source: NBS Report, 2019, p. 12)

One of the frequently raised challenges surrounding BIM adoption suggests that BIM is more useful for as well as used by large organisations. The underlying reason stems from the considerable investment and training needs in order to support BIM implementation and the fact that added complexity of construction projects carried out by large organisations arguably enhances the amount of benefits derived from effective BIM use. These arguments were to some extent supported in NBS Report (2019). As shown in the Figure below, the rate of adoption of BIM in small practices has been

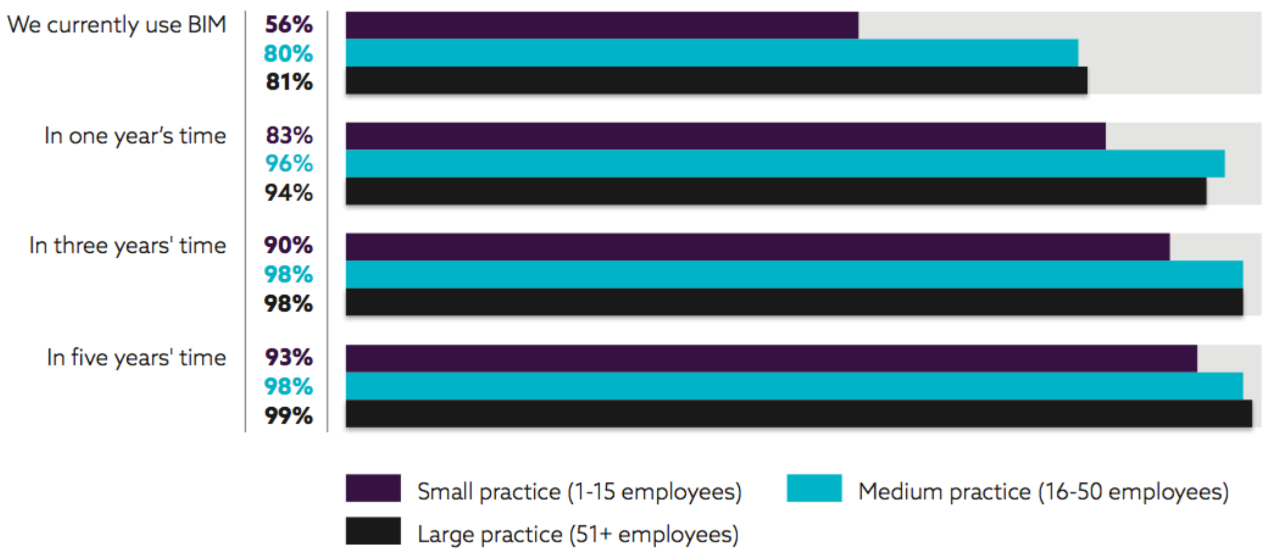

Figure: Current and projected BIM usage by practice size (Source: NBS Report, 2019, p. 14)

considerably lower in comparison to large practices (56% and 81%, respectively).

Appendix 2 – Search Criteria

General Searches (Google Scholar since 2015)

- (“supply chain" and "barriers to innovation") and "construction supply chains" [n =5]
- (“supply chain" and "barriers to innovation") and "construction” and “digital” [n =368]
- (“supply chain" and "barriers to innovation") and "construction” and “digital” and ("systematic literature review") [n =35]

Innovation Technology-based Searches (Google Scholar since 2015)

- (“supply chain" and barrier or adoption) and (digital or BIM or BIM library or BIM for FM) and ("systematic literature review") [n =32]
- (“supply chain" and barrier) and (digital) and (construction) and (Process optimisation and process improvement or efficiency) and ("systematic literature review") [n =1,640]
- (“supply chain" and barrier or adoption) and (digital) and (construction) and (data or "common data” or “data environment” or "digital twin” or “AI” or “machine learning” or “big data”) [n =10]
- (“supply chain" and barrier or adoption) and (digital) and (construction) and [n =9]
- (“supply chain" and barrier or adoption) and (digital) and (“construction process” or “construction method” or “MMC” or “modern method”) [n =7]
- (“supply chain" and barrier or adoption) and (digital) and ("lean construction” or “waste in construction") and ("systematic literature review") [n =15]
- (“supply chain" and barrier or adoption) and (digital) and (construction) and (“collaborative planning” or “collaboration” or “communication”) and (systematic literature review) [n =430]
- (barrier or adoption) and (digital) and (construction) and (modularisation or component or standardisation or "kit of parts” or “sub-assembly”) [n =3]
- (“supply chain" and barrier or adoption) and (digital) and (construction) and (offsite or onsite or manufacture) and (systematic literature review) [n =611]
- (“supply chain" and barrier or adoption) and (digital) and (construction) and ("Augmented reality” or “VR” or “virtual reality”) and (systematic literature review) [n =204]
- ("optimising machinery" OR "plant reduction” OR “plant efficiency”) and "construction industry" and "digital" and barriers [n =14]
- (“supply chain" and barrier or adoption) and (digital) and (“construction industry”) and (drones) and "systematic literature review" [n =19]
- (“supply chain" and barrier or adoption) and (digital) and (“construction industry”) and ("Computer Numerical Control” or “3D printing” or automation) [n =28]
- (“supply chain" and barrier) and (digital) and ("construction industry") and (Sensors or “Remote sensing” or “internet of things”) [n =27]
- (“supply chain" and barrier or adoption) and (digital) and (“construction industry”) and (GIS) and "systematic literature review" [n =54]

Appendix 3 - Existing Collaborative Research, Development and Demonstration Landscape

Integration of Digital Engineering	**Digitally Enabled Design** e.g. BIM, BIM libraries, digital process and design management,	**Digital Enabled Procurement** e.g. Supply chain data analytics, blockchain and cloud computing, collaborative planning and integration	**Digitally Enabled Manufacture / Sub-assembly** e.g. Modern Methods of Construction (MMC), lean and Industrialised manufacture and robotics)	**Digital Construction / Smart Sites** e.g. drones, computer numerical control, 3D printing, automation, augmented reality, digital skins	**Digital FM / Digital Twin** e.g. sensors, BIM FM, locational GIS, remote sensing or internet of things innovation
Basic Research and Knowledge Development (Academia TRL1-3) **Cdbb Investments / ESRC - Network Plus (2.5m) / EPSRC – Future Leaders**	• **D-COM: Digitisation of Requirements, Regulations and Compliance Checking Processes in the Built Environment** - Tom Beach [n =Circa £500k] • **Housing Digital Built Britain** - Gemma Burgess [n =Circa £500k] • **Vision Network: Augmented Reality and Virtual Reality for Digital Built Britain Manuel** - Davila Delgado [n =Circa £500k] • **Network FOuNTAIN: Network For ONTologies And Information maNagement in Digital Built Britain** - Peter Demian [n =Circa £500k] • **General Research projects - Co-Creating a City-Scale Digital Strategy and Framework**: A Systems and Co-production Approach - Dr Ges Rosenberg [n =Circa 300k] • **Digital Modelling of the Evolution of the Built Form in Britain** - Dr Ying Jin [n =Circa 300k]	• **Pedagogy and Upskilling** - Jason Underwood [n =Circa £500k] • **Methodologies for Planning Complex Infrastructure under Uncertainty** - Chris Dent [n =Circa £500k] • **NetworkPlus (Transforming Construction)** A new national community to unite and transform UK construction industry business models [n =£1.5m] • **Improving the Performance of Infrastructure Construction through Multi-Dimensional Benchmarking** [n =Circa ~ £100k] • **Putting people at the heart of future social housing design and manufacture** [n =Circa ~ £100k] **Digital Enablers for Construction Transformation** (Decont) – A new paradigm for rethinking construction [n =Circa ~ £100k]	• **Immediate (Integrated Management of Margins through Evaluation, Design, Analysis, Tracking and Negotiation)** - Prof Claudia Eckert [n =Circa 300k] • **Challenging Space Frontiers in Hospitals** – Accelerating capabilities and advancing business models for MMC [n =Circa ~ £100k]	• **Open ML Training Data For Visual Tagging Of Construction-specific Objects (ConTag)** - Dr Jan Boehm [n =Circa 300k] • **Integrating Conversational AI and Augmented Reality with BIM for faster and collaborative on-site Construction Assemblage (Conversational-BIM) -** The adoption of BIM by on-site frontline workers for assembly of manufactured building components to increase the productivity gained from using BIM for design and manufacturing phases of the process. On-site frontline workers spend more time interfacing with BIM tools than they spend on completing the actual assembly tasks. This project aims to utilise Augmented Reality (AR) for providing visual support to access BIM systems and installation guides without obstructing or distracting the view of onsite workers [n =Circa £1m]. • **Manufacturing integrated building components using digital hybrid Concrete Printing (HCP) technology** - This project will develop the next generation, Hybrid Concrete Printing (or HCP), technology that uses 3D Concrete Printing to create a near-net-shape (an object slightly larger than the desired object) and then use subtractive processes (cutting, milling and drilling) to remove a small amount of material to create the net-shape - the desired object to sub-millimetre precision. HCP technology will enable the intelligent integration of building performance and energy production and storage technologies, freed from traditional constraints on form and finish [n =Circa £1m]. • **Applied Off-site and On-site Collective Multi-Robot Autonomous Building Manufacturing** - Robert Stuart-Smith / Jacqueline Glass, UCL. This project will develop an innovative multi-agent control framework that enables a team of robots to operate in a similar way to how social insects, such as termites, work - collectively designing and build structures of substantial scale and complexity; by quickly and efficiently organising themselves while also providing	• **Recommendations for Automated Checking of Regulations and Requirements Management in Healthcare Design** - Prof Patricia Tzortzopoulos [n =Circa 300k] • **Analysing Systems Interdependencies using a Digital Twin** - Prof Jennifer Whyte [n =Circa 300k] • **Energy Planning for Resilient Decarbonization** - Dr Ruchi Choudhary [n =Circa 300k]

				flexible, scalable coordination of many parallel tasks [n =Circa £1m]. • **Automating Concrete Construction (ACORN)** – This project will use Innovative digital tools and techniques to optimise the shape, layout, structure and façade of buildings during the design phase. It will extend this approach downstream in the building process, to encompass fabrication [n =Circa £1m].	
Collaborative Technology and Prototype Development (TRL2-6) **InnovateUK Collaborative Research and Development (£13.3million) / Other Strong Existing Industry Partnerships Bidding / Construction Innovation Hub Platform Design Comp.** **Business Development, Equity Investment and Operation (TRL6-9)**	• **PLC Big Data and Machine Learning-enabled Automated BIM for Projects (Auto-BIM): A Common Data Collaborative System for Improved Project Performance** (In compliance with BIM standards (e.g. automated naming, population, sharing and learning), this research will ascertain the exact-level of (and the specific) information required for assets by learning from previous project lessons/historic data to create an innovative tool (Auto-BIM) as a plug-in to BIM-tools [n =£609k Prototyping]. • **AEC Delta Mobility** (A new open-source collaborative ecosystem for open specifications, compatibility, interoperability, and data exchange between engineering practices and construction firms. Standardisation and paid micro-services (with support from UK BIM Alliance and Building Smart International), will define and specify new technology (e.g. Speckle Works and 3D Repo with proprietary systems) to secure and	• **Digitally Connected Supply Chains** (A methodology and digital procurement platform to digitally connect the construction manufacturing and built environment supply chains to be outcome, asset lifecycle and quality driven to understand the minimum viable product, measure benefits and dynamically benchmark) [n =£331k Prototyping]. • **Digital planning and supply chain management toolbox for productive project delivery (PLASMA)**. Develop and test approaches to effective digital and automated planning and supply chain collaboration. A new spin-out will use 'blockchain' enabled smart contracts and timely payments, on-site sensor networks and supply chain tagging/tracking systems to increase capacity and automation. Secure data will be shared (e.g. task status/completion, component location) to develop planning scenario optimisation and industry-wide KPIs [n =£591k Prototyping]. • **Project Data Analytics Community** (working across construction policy makers, clients, contractor and consultants to develop	• **Creation of a Hybrid Insulated Structural System to Enable Delivery of a Disruptive High Volume House Building Model** (The development and field testing of prototype materials, and a factory-based process, for production of finished, non-combustible, pre-insulated structural panels for house walls, roofs and floors. BIM protocol and traceable build quality. [n =£116k Prototyping]. • **Increasing Productivity and Quality in Mass House Building** (Model-TS1, energy optimisation hardware and software, interchangeable kit of parts enabling the homedweller to adapt their own space according to their needs) [n =£629k Prototyping] • **Increase construction productivity using 3D computer vision & BIM to automate project progress and quality reporting** (AI-enabled solution to measure construction progress. rework and low productivity, high-quality 3D, reality capture data and using advanced machine learning techniques, the prototype will give real-time insights on project performance as well on productivity and risks) [n =£372k Prototyping] • **Optimising equipment use in construction with BIM, IoT and data analytics** Construction equipment fleet monitoring and management to Increased plant and equipment utilisation (e.g. IoT sensors, equipment usage data analytics, optimal planning). It will link equipment output to 4D BIM and visual on-site dashboard.	• **Automated Construction** (prototyping a new construction system to aid in the development of automated and continuous construction, new on-site machines and on site 'fabrication factories' which are run by smaller teams of semiskilled labour, a kit of parts, bespoke install machines or Sub Assembly Work Stations (SAWS), virtual reality headsets will be utilised, checking for clashes and potential improvements, robotic assembly methods on site) [n =£680k Prototyping]. • **Live Automated Materials Plan (LAMP)** (Digitise, use real-time sensors and predictive data algorithms and historical data to improve site communication/component/bulk material tracking and movement through complex site-based construction process planning and scheduling [n =£313k Prototyping]. • **Automatic DfMA-with-AET Design Generator (ADAGE): An Internet of Things tool to instil adoption of DFMA and AET by Building Designers** (Digital-means will be used to encourage a wider-adoption of DfMA-approach and active-energy-technologies (AET) by developing a BIM-software-plugin that automatically generates DfMA-concept-designs with AET based on key building-design-parameters from client/project brief (e.g. material choice, buildinguse/purpose, etc.). The proposed plugin will use Internet-of-Things, Blockchain-Technology, cloud-computing, artificial-intelligence and big-data-analytics. Parametric-modelling-artificial-intelligence-algorithms will use historic-data of former DfMA-designs with AET to produce new-solutions and generative component selection techniques to predict cost, time, safety, quality) [n =£496k Prototyping]. • **Digital design of building structures for optimised cost and carbon performance** (Structural engineering design practices focus primarily on cost minimisation, but optimisation of structural systems at the design stage could influence the overall life-cycle performance of buildings. A prototype will be developed into a software solution that allows structural engineers	• **Measurement and verification of built assets: a low cost scalable solution to insitu measurement of thermal performance** (Heat3D is a new technology for quickly and cheaply measuring heat loss from buildings (e.g. housing), enabling improvements in construction quality, performance and specification of insulation upgrades. This will involve the use of readily accessible technology to access the performance of critical building fabric elements such as floors, walls and roofs and enabling U-values and other thermal characteristics to be viewed, quantified and reported [n =£214k Prototyping]

	streamline data. This will be tested on three projects to engage manufacturers in the early design stages to increase pre-manufactured value addressing data workflow from consultants to the manufacturer) [n =£726k Prototyping and testing]. • **SEISMIC School Steel frame for schools** (the redesign of steel frame for school buildings with standardisation across volumetric suppliers for use in a new procurement framework for DfE. Also the development of a digital configurator and link to other components) [n =£650k prototyping].	a Data Trust that will harness expertise from across industry and academic partners to leverage advanced machine learning and artificial intelligence techniques).	Earlier adoption in HS2 (i.e. estimation/selection, deployment, coordination, and visualisation). [n =£174k Prototype demonstration]. • **Intelligent DEsign for Manufacture and Assembly of built assets (IDEMA)** (A new approaches to home construction and the use of active energy technologies. It will support the innovative design of a thermal efficient building with many active energy components to generate electricity. It will design in all services (water, electricity, digital services etc) as part of the PMB process. The ultimate aim is to complete a 3000 sq.foot building within 10 days.)[n =£211k Prototyping] • **AI-Optimised Pathways for Schedule Execution** (A novel automated 'schedule learning platform' will be developed that applies data science, AI and machine learning to thousands of previous project schedules, to benchmark and predict the most likely outcome for every task and provide optimal paths/recommendations to mitigate risks/delays [n =£641 Prototype and Testing]. • **Collaborative knowledge-based DfMA approach to build cost-efficient, low-impact and high performance houses** (An innovative cross-disciplinary collaborative approach to design, manufacture and assemble market-proof, environmentally-friendly and scalable affordable houses to meet demand. This will involve the house design and delivery for minimal life cycle costs and CO2 emissions (i.e. DfMA houses), evaluation of automation, development of benchmarks and evidence and engineering tools [n =£728k Prototyping, Testing and Demonstration]. • **AIMCH - Advanced Industrialised Methods for the Construction of Homes** (Seeks	to improve the material efficiency of steel-framed buildings will be used to advance design practice and compare between common structural typologies – e.g. structural materials (concrete, steel, timber), construction technologies (floor types) and other design parameters) [n =£209k Prototype Development]. • **Increasing Construction Sector Productivity through the use of Integrated Offsite Steel Modules** (Develop and publish, in a free online guide, design prototypes that can be used by engineers, main contractors, steelwork contractors, M&E contractors to design, manufacture and construct mainstream steel framed buildings that include integrated offsite steel modules) [n =£106k Implementation]. • **HIPER Pile** (A piling development to deep embedded retaining walls, a hybrid environmental control systems that combine ground source heat pumps and geothermal systems with rain water collection, solar thermal arrays, as well as solar PV and wind generated renewable energy to operate the system) [n =£614k prototyping] • **Project FAIRCOP - Feasibility of Converging Beam LIDAR for Improving Crane Operational Productivity** (Technical and economic feasibility and commercialisation of new laser based wind LIDAR devices and profiling (3D wind vector) and large crane use forecasting and warning techniques [n =£39k Prototyping, Demonstration, Testing and Commercialisation] • **Adaptive Learning for Zero Defects in Building Construction** (The aim of this project it to achieve the construction of buildings with zero defects. Based upon a feasibility study this project will use computer technology (mobile and cloud) and Artificial Intelligence (AI) to check site operative understanding of tasks and flag to supervisors. [n =£193k Prototyping] • **Modular Automated Roof Tile Factory (MARTF)** (Manufacturer investment in Carapace Slate, a patent-protected, bio-composite snap-fit roof tile system. This is a joint venture in machining robotics that will deliver a dynamic and repeatable 'SMART' /Industry 4.0 aligned manufacturing solution. Monitored and operated through advanced cloud-based and IoT technology) [n =£135k Demonstration] • **The Learning Camera** (Site employee productivity, quality and H&S monitoring using a web camera, site scenario and online dashboard	

			to develop concepts, prototype and trial solutions on 10-12 live housing projects in the use of digital integration, manufacturing and assembly. It will develop and commercialise digital design tools, develop new automated manufacturing systems, trial enhanced and advanced offsite systems, with new lean site processes [n =£3,172k Prototyping, testing and demonstration]. • **Construction Innovation Hub Platform Design Competition** (open call to collaborate with MTC, BRE and CDBB to advance capabilities around existing solutions and new ideas to advance standard product family architectures, to advance manufacturing process to test and validate solutions and deliver digital over an assets whole lifecycle) [n =£59m prototyping / platform development]. • **AIMCH** (Barrett working with its supply chains to industrialise off-site housebuilding and collect data to prove the business case. Advancing skills, ageing, productivity, output and affordability through new design tools, advanced manufacturing and lean site tools) [n =£6.5m].	to automate situational and preventative alerts [n =£190k Prototyping] • **CORE (Concrete curing prediction and schedule Optimisation for Resource Efficiency).** To understand and accurately predict concrete curing time and so with greater certainty accelerate subsequent build and fitting activity based on site-specific complex variables and a reduction in human error. To reduce time wastage, fines and poor productivity [n =£450k Prototyping and Testing]. • **AROPCQA – Augmented Reality for Operative Productivity & Continuous Quality Analysis.** A digital technology platform to understand process workflows for construction operatives. It will support correct, efficient and error free installation. Errors and associated rework will be predicted at design stage through vision and digital technologies such as augmented, virtual and mixed reality, laser scanning, computer vision, ubiquitous wireless communications and 3D digital design technologies. This will be demonstrated on nuclear reinforcement cage production, residential and commercial fit-out, and the manufacture of precast modules [n =£362k Prototype and demonstration].	

Appendix 2 – Description of the Existing Literature on the Barriers to Digital Technology Implementation

Below is a description of the current literature on the "barriers to innovation" in the use of “digital technologies” throughout the "construction supply chain". The search emphasised sources that were empirically grounded in case studies or systematic literature review and stratified across various digital enabling technologies according to those prioritised by GIRI.

General Search

Author	Title	Channel	Aim	Notes	Status
Alfar (2016)	Integration of Innovation in Construction Management	MSc	This study applies the concept of innovation management in the construction industry by studying the major components of innovation process which include the major drivers to innovation, barriers and obstacles that prevent innovation, the enablers that motivate innovation, the practices of innovation, and the benefits of innovation related to project and firm level.	Barriers from literature. No empirical evidence	Discarded
Cordeiro et al (2019)	Theoretical proposal of steps for the implementation of the Industry 4.0 concept.	Article	The purpose of this paper is to present a proposal of steps for the implementation of Industry 4.0 in the industrial context, considering management and operational aspects [n =e.g. Barriers]. The reason is to discuss that technological change is accompanied by many organizational implications, in which it is perceivable that some companies already experience strategic and operational turbulence due to the lack of understanding of the this structure’s complexity	Literature review citing various papers	Grade A
Hanna (2015)	Innovation timelines from invention to maturity	Report	The UKERC technology and policy assessment (TPA) research theme was set up to address key controversies in the energy field and to provide authoritative inputs for policy-making processes through accessible and credible reports that set very high standards for rigour and transparency.	Literature review – cites key authors from various concepts	Discarded
Ivanov (2018)	Digital Innovation in Manufacturing Firms: a GT Approach for Identifying a Barrier Typology	Article	The paper follows a case-study design with in-depth analysis of which barriers manufacturing firms face for the implementation of DI and discuss the perceive innovation type of DI.	Empirical Study, albeit in manufacturing. Good list of barriers	Grade A
Molinillo (2017)	Organizational adoption of digital information and technology: a theoretical review	Article	This paper aims to review previous studies on how organizations, particularly small and medium enterprises (SMEs), adopt digital information and technology, especially on the drivers and the outcomes of the adoption itself.	Literature review – not directly relevant	Discarded
Orzes et al (2018)	Industry 4.0 Implementation Barriers in Small and Medium Sized Enterprises: A Focus Group Study.	Article	The goal of this paper is to empirically investigate the main barriers and difficulties faced by small and medium sized enterprises in Industry 4.0 implementation. We perform a systematic literature review on the topic and conduct some focus group studies in four countries (USA, Italy, Austria, and Thailand).	Literature review and empirical focus groups	Grade B
Rose (2019)	Firm-level barriers to construction product innovation adoption according to position in the supply chain	Article	The purpose of this study is to examine product innovation as a means of addressing infrastructure shortages in developed economies and to improve the sustainability of infrastructure. The obstacles to product innovation in the road industry are compared between different types of participants in the supply chain to provide guidelines for interventions to improve innovation rates.	Literature and Empirical Case Study – specific to Construction	Grade A
Shelton (2016)	Implementation of innovative technologies in small-scale construction firms Five Australian case studies	Article	The purpose of this paper is to assess whether the Australian construction industry is providing an environment where user-based innovation is being supported and implemented.	Literature and Empirical Case Studies	Grade A

The following table provides a detailed description of literature-specific barriers for selected key references.

Digital technology	**Ivanov (2018) Digital Innovation (Explicit and Implicit Barriers)**	**Cordeiro et al (2019) Industry 4.0 concept.**	**Orzes et al (2018) Industry 4.0 Barriers in SMEs**	**Rose (2019) Road construction industry**	**Rose (2014) Road construction industry**
Ecosystem and Market Barriers (Industry readiness, low customer acceptance, new professional	**Ecosystem Barriers – Industry readiness for digital innovation** (e.g. industry structure, standards for connectivity, not scalable and network effects are not possible, limited industry trend) **Digital Innovation Maturity of the Market Barriers – Low customer acceptance** (e.g.	**New Professional Profile Barriers** (e.g. new disciplines, new knowledge and skills, new strategies and culture for sharing good practice)	**Competencies / Resources Barriers** (lack of skilled employees, lack of technical knowledge and system complexity, need to find suitable research partner)	**Contractor Product Innovation Barriers** (e.g. Restrictive tender assessment criteria (e.g. price-only), Insufficient involvement of contractors early in the design phases of a project, and Adversarial contract relations	**Procurement Systems** (Restrictive tender assessment criteria (e.g. price-only). New product ideas that save project cost, but impose higher costs over the life of the asset. Incentives that favour new products that save project cost, over new products with other types of benefits. Insufficient

capabilities, communication networks, lack of resources, lowest price procurement, testing, industry relationships)	innovation is not accepted by customers, customers do not recognise value)	**Communication Networks** (e.g. Effectiveness of connectivity infrastructure that allows access to shared data, data quality and real-time data flow and integration)		that inhibit adoption of new products on projects). **Client Product Innovation Barriers** (e.g. Difficulty in getting suppliers of new products to conduct sufficient testing prior to presentation to their clients, Disagreement between industry participants over who carries the risk of new product failure. And Difficulty in getting suppliers of new products to accept extended warranties to cover increased risks associated with new products)	involvement of contractors early in the design phases of a project. Infrequent use of performance-based specifications by the client. Insufficient involvement of suppliers early in the design phases of a project. Lack of clear procedures with the client for assessment of new product ideas). **Industry Relationships** (Disagreement between industry participants over who carries the risk of new product failure. Adversarial contract relations that inhibit adoption of new products on projects. Disagreement over the appropriate period for new product warranties. Disagreement between industry participants over who is responsible for testing new products).
Policy, Regulation and Legal Barriers (GDPR, procurement, IP, required legislation, data security, duplication of policy development)	**Legal Barriers – Uncertainty due to governmental regulations for digital innovation** (e.g. GDPR, Procurement and IP)	**Legislative / Regulations Barriers** (e.g. Need for development of specific technology legislation, corporate data protection and accountability) **Safety Barriers** (e.g. data security risk factors and the dynamic sharing, collaboration, and mobility of large data volumes and various sources)	**Legal** (data security concerns)		**Regulatory Conditions** (Heavy reliance on tightly prescribed/restrictive specifications by the client. Duplication of trialling effort to meet the needs of different clients and agencies).
Organisational Innovation Strategy, Collaboration and Process Barriers (weak innovation processes, weak collaboration, lack of strategy and challenge, lack of standardisation, change management, new business models, lack of testing, restricted lowest price- tendering, time pressure to work on fee paying jobs)	**Innovation Process Barriers – no integration possible in the current framework for digital innovation** (e.g. investments made from a product development perspective, requirements for quality, no dedicated process for development) **Innovation Process Barriers – No integration possible in the current framework** (e.g. digital innovation is not made open, innovation has weak involvement with customers) **Organisation Barriers – Blurred direction and lack of alignment towards the development of digital innovation** (Lack of strategy, organisational change, challenging roadmap, internal alignment)	**Lack of Standardisation and Reference Architectures** (concepts are still under construction. Limited strategy and no standardisation of technical aspects) **Organisation and Process Changes Barriers** (e.g. new types of work and support organisation, collaborative working environment, knowledge management)	**Implementation Process** (need for new business models, lack of methodical approach for implementation, high coordination effort)	**Consultant product innovation Barriers** (New product ideas that save project cost, but impose higher costs over the life of the asset, Incentives that favour new products that save project cost, over new products with other types of benefits. And contractor time pressure inhibiting the ability to consider new product ideas) **Supplier Product Innovation Barriers** (e.g. Restrictive tender assessment criteria (e.g. price-only), Insufficient involvement of suppliers early in the design phases of a project, and difficulty in getting the client to trial new products).	**Organizational Resources** (Contractor time pressure inhibiting the ability to consider new product ideas. Time pressure within the client inhibiting ability to consider new product ideas. Difficulty in getting the road agency in your state to trial new products. Difficulty in getting suppliers of new products to conduct sufficient testing prior to presentation to their clients. Difficulty in getting suppliers of new products to accept extended warranties to cover increased risks associated with new products. Lack of expertise on the part of new product suppliers (manufacturers, distributors, contractors or consultants) to accurately assess the performance capability of new products. Lack of expertise within the client to accurately assess the performance capability of new products. Lack of client expertise to accurately assess the performance intention of prescriptive specifications. Inequities in the treatment of different types of new product suppliers (e.g. lone inventors, large manufacturers, head contractors and subcontractors) by the client)

Economics and Finance Barriers (few tangible incentives, fast pace of projects, high investment, lack of available resources and ROI)	**Capitalization Barriers – Lack of tangible incentives to invest in digital innovation** (e.g. capitalization cannot be defined, pace is very high and cannot fit the business model)		**High Investment Barriers** (e.g. Large investment in Infrastructure and capacity building)	**Economic/Financial** (high investments required, lack of monetary resources, lack of clearly defined economic benefits)		
Technical Technology Barriers (focus on technology, different levels of maturity, lack of standards, compatibility and infrastructure)	**Technology Readiness Barriers – Pace of technology** (e.g. technology alone cannot drive the development of digital innovation)		**Technology Barriers** (e.g. different levels of maturity, early stage modelling)	***Technical Barriers*** (lack of standards, uncertainty about the reliability of the systems, weak IT infrastructure, difficult interoperability / compatibility, technology immaturity)		
Data Barriers (Processing, storage, cleaning)			**Data Processing Barriers** (e.g. the enormous amount of data and diversity of sources, demanding storage capacity, data processing and cleaning and management)			
Culture and Management Barriers (misunderstanding of digital, senior management, engagement and resistance)	**Explicit Cognitive Barriers – Misunderstanding of digital innovation** (e.g. perception by senior management level, Hesitate due to lack of experience, Software engineers are not attracted, Lack of knowledge, Not understanding the potential, Mind-set)	**Implicit Cognitive Barriers – misunderstanding of digital innovation** (e.g. considered a hype and different expectations)	**Employee Engagement** (e.g. resistance to change and fear of exchanging people for smart equipment. Difficult to accept technology and knowledge accessibility)	**Cultural** (lack of support by top management; preferred autonomy)		

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Barriers to Digitally Enabled Design (DT Digital, BIM, BIM library Innovation, digital process and design management optimisation innovation)

Author	Title	Channel	Aim	Notes	Status
Goulding et al (2015)	New offsite production and business models in construction: priorities for the future research agenda	Article	This paper summarises the work of TG74, where people, process and technology drivers were investigated for construction, manufacturing and design and mapped against three levels of priority and three timeframes.	Lack of description of barriers	Discarded
Waller (2013)	Data science, predictive analytics, and big data	Article	We illuminate the myriad of opportunities for research where supply chain management (SCM) intersects with data science, predictive analytics, and big data, collectively referred to as data science, predictive analytics, and big data (DPB).	No explicit barriers for process optimisation	Discarded
Love (2004)	A seamless supply chain management model for construction	Article	Presents a holistic approach to project SCM and model that integrates design and production processes.	No explicit barriers for process optimisation	Discarded
Dallasega (2018)	Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review	Article	Construction supply chains (CSCs) have specific characteristics, such as being temporary organizations that require high coordination efforts to align the processes of supply chain actors. This article presents a framework for explaining Industry 4.0 concepts that increase or reduce proximity. This framework is based on the results of a systematic literature review of scientific papers and analysis of applicability through practical publications and examples from industrial case studies.	No explicit barriers for process optimisation	Discarded
Büyüközkan (2018)	Digital supply chain: literature review and a proposed framework for future research	Article	This article reviews the state-of-the-art of existing Digital Supply Chain (DSC) literature. It identifies key limitations and prospects in DSC, summarizes prior research and identifies knowledge gaps by providing advantages, weaknesses and limitations of individual methods The article also aims at providing a development framework as a roadmap for future research and practice.	Partial expression of barriers relating to the digital supply chain – outside of construction	Grade C
Govindan (2018)	A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective	Article	This study provides an analysis of the drivers, barriers and practices that influence the implementation of the circular economy in the context of supply chains through a systematic review. In order to analyse the circular economy's level of implementation, we correlate stakeholders' perspectives with drivers, barriers, and practices; thus, a multi-perspective framework is proposed.	No explicit barriers for process optimisation	Discarded

Oesterreich (2018)	Understanding the implications of digitisation and automation in the context of Industry 4.0	Article	This paper explores the state of the art as well as the state of practice of Industry 4.0 relating technologies in the construction industry by pointing out the political, economic, social, technological, environmental and legal implications of its adoption.	Barriers in the implementation of industry 4.0	Grade B
Marchi (2017)	Supply chain management for improved energy efficiency: Review and opportunities	Article	This paper aims to provide a systematic review of papers on the integration of energy efficiency in supply chain design and management published in academic journal, thereby defining potential research streams to close the gaps in the literature.	Not directly relating to process optimisation barriers	Grade B
Bressanelli (2018)	Challenges in supply chain redesign for the Circular Economy: a literature review and a multiple case study	Article	A multiple case study in the household appliance supply chain is carried out, to explore how these challenges appear in practice and how companies may tackle them. The cases analysed involve actors at different supply chain levels, and findings suggest that a great degree of vertical integration by one actor in the supply chain is not a necessary condition for Circular Economy implementation.	Empirical and literature-based barriers	Grade A
Shibin (2016)	Enablers and barriers of flexible green supply chain management: a total interpretive structural modelling approach	Article	In this paper an attempt has been made to build a theoretical framework of the enablers and barriers of flexible green supply chain management (FGSCM). Ten enablers and eight barriers of FGSCM are identified through an extensive literature review process, then the complex interrelationship between enablers and barriers are modelled to show how they impact the design and implementation of flexible and green strategies in a supply chain closed loop system	Empirical and literature-based barriers	Grade B
Musa (2016)	A review of RFID in supply chain management	Article	This paper presents a systematic literature review of papers that were published in academic journals on the applications of radio frequency identification (RFID) in supply chain management between the years 2000 and 2015.	Limited expression of process optimisation barriers	Discarded
Calatayud (2019)	The self-thinking supply chain	Article	This paper aims to both bridge the gap between the practitioner and academic literature on these topics and contribute to both practice and theory by seeking to understand how such developments will help to address key supply chain challenges and opportunities.	Focus outside of construction and weak description of barriers	Discarded
Parida (2019)	Reviewing literature on digitalization, business model innovation, and sustainable industry	Article	This special issue editorial attempts to take stock of the emerging research field through a literature review and providing a synthesis of special issue contributions. In doing so, we contribute by developing a framework that communicates and sets the direction for future research by linking digitalization, business model innovation, and sustainability in industrial settings.	Few barriers expressed. Outside of construction.	Discard

The following table provides a detailed description of literature-specific barriers for selected key references.

DT Digital, BIM, BIM library Innovation, digital process and design management	**Büyüközkan (2018) Digital Supply Chain (DSC)**	**Oesterreich (2018) Industry 4.0**	**Marchi (2017) SCM & Energy Efficiency**	**Bressanelli (2018) Supply Chain Redesign**	**Shibin (2016) Green Flexible Supply Chain**	**Vennstrom (2009) Client Change to Con' Process**	**Erik Eriksson (2008) Barriers to Partnering**	**Abdul-Hadi (2005) Bus' Process Re-eng' (BPR)**	**Bibby (2003) Barriers in DM**
Ecosystem and Market Barriers (unclear benefits, few incentives, cannibalisation, IP and know-how, brand image, lack of leadership, existing culture of claims and design management)		**Hesitation to adopt** (High investment costs of new technologies and the unclear benefits, construction companies are hesitating to invest in them. Few incentives for the adoption (e.g. government mandates for BIM use and funding programs for industry and research)		**Market and Competition** (Cannibalisation, IP and know-how access, Brand image)	**Inadequate Customer Focus**	**Industrial barriers** (traditional organization of the construction process, conservative industry culture, industry structure and traditional production processes)		**Using external consultants in BPR effort** **Rapid change of external environment**	**Pre-application** (Lack of leadership, no agreed design management process, client ignoring design freeze/change control, Inflexible construction programme, Commercial decisions affecting design, Construction team ignoring design freeze/change

									control, Inflexible client programme, Parties not collaborating)
Policy, Regulation and Legal Barriers (ethics and legal views of tracking and monitoring, ownership and IP, responsibility for errors, taxation, lack of standards, traditional procurement procedures**)**		**Regulatory Compliance** (Ethical and legal concerns about the tracking and monitoring of employees as well as the handling of the recorded information) **Legal and Contractual u**ncertainty (Legal and contractual uncertainty concerning the use of BIM. For example, questions of the legal ownership of the model and the legal responsibility for errors and problems with the model have to be answered)		**Standards and Regulation** (Taxation and incentives, Measures, metrics and indicators, Lack of standards)	**Poor Government Support**	**Institutional barriers** (standard contracts, laws and traditional procurement procedures)	**Industrial Barriers** (Traditional procurement procedures, Laws and regulations, Rules and standard contracts)	**Laws and regulations External resistance**	
Organisational Innovation Strategy, Collaboration and Process Barriers (lack of planning, length and inflexibility of supply chain, lack of collaboration and integration, process change, innovation in supply chain partnerships, supply chain expertise, leadership, shared risk)	**Lack of planning** (Deficiency of proper demand plan and guidelines and tools) **Length, volatility and inflexibility of the supply chain** (The supply chain involves internal and external partners making it slow and prone to errors. Lack of required flexible and agile supply chain management. Reliance on certain suppliers). **Lack of collaboration** (Deficient collaboration with external associates and deficient input from internal functions **Lack of integration** (Deficient view on the integration of digital and non-	**Organisational and Process Changes** (The implementation of new technologies must take place at all levels of the organisation and requires the re-evaluation and re-engineering of business practices)	**Organisational Barriers**	**Supply Chain Management** (Return flows uncertainty, transportation and infrastructure, Availability of suitable supply chain partners, Coordination and information sharing, Product traceability, Cultural issues (linear mind-set)	**Lack of Expert Supply Chain Professionals**		**Organisational Barriers** (Focus on projects instead of processes, labour unions, New competencies are required, Traditional organisation of the construction process)	**Observing failure cases of other BPR efforts Undefined core processes Inappropriate benchmarking (goals) Believing that change doesn't add value to shareholders Following inadequate approach Vertical structure of organization Lack of commitment from top management Unwillingness to share risk equitably Culture of construction firms**	**Selection** (Responsibility of other management function, does not help manage the design process, not suitable to D&B)

	digital supply chain management								
Economics and Finance Barriers (high cost of equipment, unclear benefits, lack of business evaluation, complexity of the construction site-based environment, access to capital, financial risks, overoptimistic demand forecasts)	**Wrong demand forecast** (Inaccurate over optimistic forecasts for demand, inventory, production and other data)	**High Implementation Cost** (High cost for technical equipment, for training and education, and for external consultancy fees. Unclear benefits and prediction of cost savings and a lack of consistent fiscal benchmarking to evaluate the business improvements and gains) **Higher Requirements for Computing Equipment** (Higher requirements for computing equipment for the use in the specific construction site environment (mostly outdoors, dust and moisture) have to be taken into account. For example, mobile devices should be designed to handle strong vibrations, large falls and humidity).	**Economic Barriers** (Access to Capital, including a lack of awareness (especially in terms of life cycle cost effects), high investment costs, hidden costs and low profitability)	**Economic and Financial Viability** (Time mismatch between revenue and cost streams, Financial risk, Operational risk)	**Financial Barriers**			**Lack of resources (time, money, staff, etc.)** **Difficulty of measuring benefits compared to BPR costs**	
Technical Technology Barriers (Lack of standards, incompatibility, reference architectures, lack of SME capability, technology management, infrastructure)		**Lack of Standards and Reference Architectures** (A lack of standards e.g. a lack of complete and international standard for RFID technology and multi-protocol tags and readers, or a lack of consistent BIM standards (software incompatibility). Furthermore, there is a need for an industry-specific reference architecture for Industry 4.0.	**Technology Barriers** (SMEs present lack of internal skills to interpret technical information and the time and capacity to plan they also perceive a “cultural” barrier to participation)	**Technology** (Eco-efficiency of technological processes, Product technology improvement, Data privacy and security) **Product Characteristics** (Fashion change, Product complexity, Product (mass) customisation)	**Poor Environmental Awareness** **Poor Technology Management**			**Absence of Information Technology (IT)** **Weak infrastructure** **Using inappropriate tools**	
Data Barriers (lack of information sharing, developing a software architecture, data sharing across supply chain, knowledge	**Lack of information sharing** (Companies’ reluctance on information sharing. The belief that everything will be fine)	**Knowledge management** (The temporary nature of the construction projects and the fragmented characteristics of the construction value chain are reasons for the lack of codified and shared project knowledge and limited	**Information-related Barriers** (e.g., not sufficient information on costs, benefits and technologies)					**Lack of knowledge about BPR**	

management, data security)	**Data Barriers** (Gathering all required data from many disparate sources and ensuring the accuracy of that information and developing a software architecture and platform that can use the data to manage and execute the supply chain).	standards for knowledge management. **Data Security and Data Protection** (growing data volumes, the increasing demand for mobility, collaboration and sharing information with external partners. Increasing need for data security and data protection)							
Culture and Management Barriers (deficiencies in supply chain management training and skills, low technical competence, fast and reliable connectivity, resistance to change, lack of awareness, reputation, usage, coordination, short-term view of ethics, adversarial attitudes, empowerment, leadership)	**Lack of knowledge** (Deficiency of supply chain management training and skills)	**Need for Enhanced Skills** (Due to the low technical competency of the construction workers on site, there will be an increasing need for staff training and development as well as the increasing need for integration skills. New competencies are needed to optimise the project organisation and to attract new talents to the workforce) **Existing Communication Networks** (Use of information and communication technologies requires a fast and reliable Internet access on construction sites. Hence, unreliable broadband connectivity or the lack of access to high-bandwidth connectivity for collaboration applications) **Acceptance** (Strong resistance to changes and new technologies as well as the conservatism and inability to adapt by staff members of its companies. Concerns over job-loss.	**Behavioural and Competency-related Barriers and Lack of Awareness** (enterprises perceive themselves as proactive. In particular, larger organizations present more strategy, time and capacity to act and reactive to issues affecting their reputation).	**User' Behaviour** (Ownership value, Careless behaviour in product usage, Users' willingness to pay)	**Poor cooperation and Improper Communication Among Suppliers Risk-averse Attitude**	**Attitudinal barriers** (adversarial attitudes, lack of ethics and morality, focus on projects instead of processes and a short-term focus)	**Cultural Barriers** (Short-term focus, Adversarial attitudes, Conservative industry culture, Lack of sub-supplier involvement in specification)	**Limited vision of construction firms Absence of amnesty Top management fear of empowered employees Bureaucracy Fear of failure by top management Downsizing associated with BPR effort Fear of losing jobs by employees Affected people not informed Employees resistance to change Resistance by middle managers because of fear of losing their jobs**	**Application barriers** (Lack of leadership, Construction team ignoring design freeze/change control, Client ignoring design freeze/Change control, Parties not collaborating, No agreed project design management process, Inflexible construction programme, Insufficient design resources, Commercial decisions / lack of decisions affecting design, Insufficient design management, Designers lacking required skills, Inflexible client programme).

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Barriers to Digital Enabled Procurement (project data analytics, storage and data environments innovation, supply chain integration)

Author	Title	Channel	Aim	Notes	Status
Madanayake (2019)	Critical analysis for big data studies in construction: significant gaps in knowledge	Article	The purpose of this paper is to identify the gaps and potential future research avenues in the big data research specifically in the construction industry.	Limited expression of barriers	Discarded
Arunachalam (2018)	Understanding big data analytics capabilities in supply chain management	Article	This paper aims to provide a systematic literature review of BDA capabilities in supply chain and develop the capabilities maturity model. The paper presents the bibliometric and thematic analysis of research papers from 2008 – 2016.	Full list of barriers from literature	Grade A
Barbosa (2018)	Managing supply chain resources with Big Data Analytics	Article	In the light of the Resource-based View, the main goal of this study was, by means of a systematic literature review, to comprehend how BDA has been investigated on SCM studies, which resources are managed by BDA as well as which SCM processes are involved.	Limited expression	Discarded
Li (2019)	Blockchain in the built environment and construction industry	Article	The overarching aim of this study was to analyse the current state of DLT in the built environment and the construction sector with a view to developing a coherent approach to support its adoption specifically in the construction industry.	Full list of barriers from literature	Grade A
Shi (2016)	Mobile Internet based construction supply chain management	Article	This paper presents a systematic review on M-Internet based CSCM via descriptive and thematic analyses of publications retrieved from four major databases. The theoretical contribution of this paper is the development of an integrated framework in this research domain. This includes five aspects of CSCM, i.e. material flow and supply management, real-time information sharing and communication, coordination and integration in CSC, technology support for M-Internet, and associated safety issues	Limited definition of the specific barriers	Grade B

Chong (2014)	An explanatory case study on cloud computing applications in the built environment	Article	A total of forty two cloud computing applications consisting of general cloud applications, Building Information Modelling (BIM), and project management cloud applications were selected and critically reviewed. A decision-making model was also developed to assist parties in selecting a suitable application.	Limited definition of the specific barriers	Grade B
Martinez (2016)	Supply chain integration opportunities for the offshore wind industry: A literature review	Article	This paper surveys the literature on supply chain integration (SCI) to identify the state of research in the various types of studied industries and manufacturing environments. The purpose of this paper is to identify academic discoveries that could provide offshore wind projects with means to overcome their current supply chain challenges.	Information and partial description of the barriers	Grade C

The following table provides a detailed description of literature-specific barriers for selected key references.

Supply Chain Data Analytics, Blockchain and Cloud Computing	**Martinez (2016) Supply chain integration**	**Li (2019) Blockchain**	**Arunachalam (2018) Big Supply Chain Data Analytics**	**Shi (2016) Mobile Internet SCM**	**Chong (2014) Cloud Computing**
Ecosystem and Market Barriers (high competitive intensity, lack of perceived need, coordination, scalability of data storage and speed)				**High competition intensity** **Lack of Perceived Needs / Weak use in decision making** **Difficulties to coordinate organizational participation of users and resources**	**Market Barriers** (Scalability of data storage and speed of growth. Policy and business aspects
Policy, Regulation and Legal Barriers (lack of contractual and legal precedence and constraints of shared reputation and confidentiality)		**Legal** (There is a lack of legal precedents and regulations. Construction relies heavily on legally binding contracts to operate and has problems with enforcing regulations)			**Statutory and Data Policy Barriers** (Data confidentiality, auditability, and shared reputation in collaborative environment
Organisational Innovation Strategy, Collaboration and Process Barriers (Collaborative information sharing, access, trust, ethics, security, competition, principle-agent conflicts, incentives, leadership culture and capabilities)	**Lack of cooperation** **Lack of inventory management visibility** **Lack of one or more of the integrative practices** **Strategy misalignment** **Lack of managerial support** **Lack of information sharing** **Non-involvement of customers in product design**	**Readiness for Adoption** (Full adoption requires information sharing and collaboration from all participants. Some of the construction industry's biggest problems centre on sharing of information, trust and collaboration)	**Getting Access to Inter-organisational Data and Data Collaboration** (Owned by different departments or organisation. Collaboration and cross-functional team formation between various stakeholders within an organisation should be a priority for implementation of big data. While forming an inter-organisational cross-functional team, the challenges that can be anticipated are competition within supply chain network, principle-agent conflicts, incentives arrangements, data sharing policies, etc. Data-driven culture, which is one of the key BDA capabilities, and fact-based management, should be encouraged across supply chain network as a strategy for effective utilisation of BDA and to create business value. Leadership also plays a significant role in successful implementation of BDA systems for SCM) **Ethical, Privacy and Security Concerns** (Big Data possess several concerns such as privacy, security, unethical use of Big Data and processing data ineffectively which would lead to	**Lack of top management support**	**Adoption aspects** (Fragmentation of practices is one of the key issues in the built environment).

			biased findings. Supply chain professionals raised concern about privacy and data security, and argued that out-dated regulations are one of the major obstacles in data sharing, especially consumer data. Privacy, security and data laws could be of serious concern for multinational supply chains, obligated to abide by the laws of different countries while sharing data across supply chains. However, these challenges could be overcome by employing effective data governance initiative within the process of data integration and management. **Problems with Access and Control of Information Sharing**		
Economics and Finance Barriers (Energy consumption, exchange rates, human error, malicious attack, timescale, resources, scaled capabilities, ROI, high software and licensing costs)		**Energy Consumption** (Massive amounts of energy are required to run Proof-of-Work protocols. This impacts the built environment regarding emissions, grid capacities and demand management) **Exchange Rate Volatility** (The value of Bitcoin fluctuated between $1000 and $20,000 in 2017. Fluctuations in cryptocurrency valuations means they are not yet stable enough for use in construction projects) **Coding of Smart Contracts** (Human error and badly coded contracts could be disastrous. All construction projects are reliant upon well executed contracts that set out all parties' obligations thereunder) **Malicious Attacks** (Different types of attacks present risks for use of DLT. Theft of data/currency pose threats to smart cities, construction projects etc)	**Time-consuming** (Predictive analytics initiative is time-consuming and includes various stages of developing, testing and adapting it to different contexts. Bringing together experts from various functions with varied mindsets will be a challenging task. In complex systems like supply chain, BDA implementation needs consistent support from top management and key stakeholders) **Insufficient Resources** (The data and analytics resource capabilities vary across firms in a supply chain network. Supply chain partners' lack of IT resources and capability to share data and information in real-time will cause discrepancies) **Issues with Return on Investment (ROI)** (Unclear benefits and ambiguity on ROI make stakeholders apprehensive about implementing BDA. Achieving financial benefits from BDA is challenging too as it depends mostly on the "downstream" employees who performs the task)		**Cost Barriers** (Costs associated with software licensing)
Technical Technology Barriers (Technology scope, requirements, scaling, demand, and risk of tampering)		**Technological State of the Industry** (There is an underlying requirement for a certain standard of technology to exist within an industry before implementation. The industry is not yet sufficiently digitalised to take full advantage of DLT. Risk of tampering of smart devices)	**Lack of Techniques and Procedures** (Incapability of techniques to exploit the data deluge properly. For instance, in the case of demand forecasting techniques, significant attention is given solely to endogenous time-serious variables for demand forecasting, and there is a lack of consideration of exogenous variables and information sources)	**The application scopes, requirements and performance of mobile technologies (e.g. VR visualization outdoors) and data use and manipulation (e.g. algorithms)**	
Data Barriers (data authentication, stability, capacity, connectivity, interoperability / compatibility, and lock-in)		**Authentication of Data Bandwidth & Connectivity** (Ensuring data uploaded to the ledger is legitimate; could cause fraudulent activity within the supply chain. Sufficient server capacity required for stability of the system along with continuous internet connectivity. Elements of the supply	**Data Scalability** (Organisations have to dump their data after a particular period so as to store newly generated data. Replacing relational databases which are limited regarding scalability with more advanced infrastructure such as Hadoop distributed databases, distributed file systems, parallel computing and cloud computing capability could be considered to tackle scalability issues. Organisations must adopt strategies to optimise data collection process and reduce unwanted data generation right from the source)		**Availability of service** **Data lock-in and data compatibility** **Technical Barriers** (Performance unpredictability. Bugs in large-scale distributed systems and lack of automation

		chain delivery system could fail with lack of connectivity) **Interoperability** (Where different applications need to communicate, there are challenges with transfer of data. This is already seen as a key challenge to Building Information Modelling in construction)	**Data Quality** (Combining, validating, and data cleansing will be a tedious which requires exhaustive commitment from the project management team) **Data Quality** (There are quality issues associated with the process of data production, which is often compared with the product manufacturing process. Poor data quality would hinder the data analytics activities and affect management decisions. Unlike a physical product, data is intangible in nature and measuring data quality is a multidimensional problem. There must intrinsic quality (accuracy, timeliness, consistency, and completeness) and contextual quality (relevancy, value-added, quantity, believe-ability, accessibility, and reputation of the data) and infrastructure quality (such as transportation system, ports, technology, etc.)		
Culture and Management Barriers (Resistance to change, skills, fear of losing competitive advantage, leadership, new roles, use of real-time data, lack of integration)		**Resistance to Change** (Implementation requires process changes at all levels of the organisation. The industry is historically resistant to change so may not realise all possible benefits of DLT) **Skills** (Given its nascence, there is a significant lack of people sufficiently trained in DLT. Fresh new talent is needed in the industry for successful implementation)	**Fear of losing competitive advantage** **Culture and Managerial Issues** (Establishment of a cultural competence across supply chains. To build transformational BDA capabilities, business and IT leaders in organisations have to work together and develop new strategies and roles such as Chief Data Officer, Data scientists to address the needs of technology and business) **Behavioural issues** (From the behavioural perspective, the use of real-time data and information could be challenging because decision makers may excessively react to even small changes in the physical world. There is risk of identifying many statistically significant but irrelevant correlations that do not have a causal linkage) **Lack of Skills and Capability for Implementing a Solution** (Inexperienced employees, time constraints, lack of integration, lack of appropriate predictive analytics solution, and issues with change management. Inability to identify suitable data, lack of either analytical skills or domain knowledge)		

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Barriers to Digitally Enabled Manufacture / Sub-assembly (construction process, MMC, lean, offsite and onsite manufacture innovation)

Author	Title	Channel	Aim	Notes	Status
Jin et al (2018)	holistic review of off-site construction literature published between 2008 and 2018	Article	This study critically reviews and summarizes the latest research keywords and main research topics in OSC and assesses the performance of OSC compared to that of conventional construction approach. It highlights the current research gaps in integrating OSC with other emerging construction concepts; and future research directions.	Limited expression of the barriers	Grade C
Delgado, et al (2019)	Robotics and automated systems in construction: Understanding industry specific challenges for adoption	Article	An investigation into the industry-specific factors that limit the adoption in the construction industry. A mixed research method was employed combining literature review, qualitative and quantitative data collection and analysis. Three focus groups with 28 experts and an online questionnaire were conducted.	Comprehensive description of the literature and barriers	Grade A
Li (2019)	Integrating building information modeling and prefabrication housing production	Article	Building Information Modelling (BIM) and Prefabrication Housing Production are integrated into a conceptual framework based on existing studies. This is based on a critical review of 65 papers published in the peer-reviewed journals from 2005 to 2017, a conceptual framework is proposed for the integration of BIM and PHP.	Interesting model, however there is no evidence of stated benefits	Discard
Liu (2019)	Trending topics and themes in offsite construction (OSC) research: The application of topic modelling.	Article	The purpose of this study is to discover the distribution and trends of existing Offsite construction (OSC) literature with an intention to highlight research niches and propose the future outline.	Limited focus on barriers	Discard
Thunberg (2017)	Categorising on-site problems: A supply chain management perspective on construction projects	Article	This study aims to identify and categorise common on-site problems from a supply chain management (SCM) perspective and to trace the origin of these problems in the construction project process, the supply chain or in the intersection between these processes. This allows for identification of how on-site problems affect SCM in construction projects and how they can be mitigated.	Excellent method of systematic review.	Grade A
Alkahlan (2016)	Integrated Design and Manufacturing [IDM] Framework for the Modular Construction Industry	PhD	The aim of this research was to map the design and modular homes manufacturing processes in an effort to better understand the relationships between these two domains.	Limited expression of the barriers	Discard
Zakaria (2018)	Contextual, structural and behavioural factors influencing the adoption of industrialised building systems: A review	Article	This paper reviews literature aimed at understanding the different influences impacting on IBS adoption. The aim of the paper is to categorise and synthesis factors identified in the literature that explicitly or implicitly impact on IBS adoption decision-making.	Limited expression of the barriers	Grade B
Cicculló (2018)	Integrating the environmental and social sustainability pillars into the lean and agile supply chain management paradigms	Article	Develops a systematic literature review addressing the integration of lean, agile and sustainable supply chain management paradigms. 73 papers are analysed, deriving 6 types of integration between lean & sustainable and agile & sustainable supply chain paradigms. To achieve each type of integration, a set of practices are highlighted.	Limited expression of barriers	Discarded
Babalola (2018)	Implementation of lean practices in the construction industry: A systematic review	Article	The implementation of lean principles and approaches is gaining grounds in the construction industry globally. However, there is no clear understanding of the number and categories of lean practices implemented and the benefits associated with it in the planning, design and construction of building and infrastructure projects. This paper relied on a systematic review of published literature in Scopus, Science Direct and Google Scholar to identify and categorize the different lean practices implemented in the construction industry and the benefits derivable from them.	Limited expression of barriers	Discarded
Sarhan (2018)	Barriers to implementing lean construction in the UK construction industry	Article	this study sought to identify and assess the possible barriers to the successful implementation of LC in the UK. Based on an extensive literature review, followed by a statistical analysis of data gained from a questionnaire survey which targeted practitioners in the UK construction industry, a number of barriers were identified as key barriers. Further analysis revealed that only three of these barriers were determined as significant.	Wide expression of barriers	Grade A

The following table provides a detailed description of literature-specific barriers for selected key references.

Modern Methods of Construction, Lean and Industrialised Manufacture and Robotics	Jin (2018) Integrated Offsite construction	Delgado, et al (2019) Robotics and automated systems	Thunberg (2017) On-site	Jiang et al (2018) Prefabricated Construction	Mao (2013) Offsite Construction	Zakaria (2018) industrialised Building Systems	Sarhan (2018) Lean and Waste
Ecosystem and Market Barriers (Incentives, government support for innovation, high initial capital cost, traditional procurement and contracts, adversarial relationships, lack of measure of quality and productivity losses, market demand, access to labour, complex supply chain arrangements, variability in projects, lack of supplier involvement and weak collaborative planning, trust, capacity and attitudes)	**Ecosystem Barriers** (Lack of incentive policy, insufficient governmental support, and fragmentation in the project delivery process caused barriers in implementing OSC)	**Market and Weak Business Case** (High initial capital investment, capital intensive, low return on investment and business models and contracts stifle collaboration. Unclear value that construction companies can obtain from adopting robotics. Low return on investment due to insufficient demand. There is no hard evidence that adopting robotics will genuinely represent a cost reduction in the delivery of assets. The construction industry is a low-profit and high-risk sector; in which this lack of evidence represents a massive obstacle. There are no complete and thorough cost/benefit studies for adopting robotics. Cost includes the robotic systems, but also software, skilled engineers, and training. Insufficient demand for robotics and automated systems. High maintenance costs). **Habitual Low Sector Productivity** (There is not a strong motivation from contractors to improve. Lack of access to labour will drive changes - easy access to labour reduces the pace at which automation is adopted. **Lack of Government Incentives** (A limiting factor for improving productivity). **Fragmented Nature of the Construction Industry** (The complex and varied supply-chain required to deliver construction projects and the poor knowledge exchange prevent adoption of robotics. The construction is a low-profit and high-risk industry, in which the adoption of new technologies is not feasible in practice and can affect the survivability of the companies). **Industry-Intrinsic Ecosystem Challenges** (Fragmentation, project-based industry structure, intense competition, high-risk, low profitability, prominence of SME's in the sector, conflicting interests in the supply chain, subpar collaboration in supply chain, poor information exchange, significant duplication of efforts, product complexity and limited use of digital modelling).	**External Communications** (Exclusion of subcontractors when planning (e.g. planning the construction project process or the supply chain), Different customer perspectives, Lack of long-term relationship, Lack of trust, Unfamiliar with the project, Lack of workflow planning, Lack of coordinating plans, Client communications, Lack of sharing knowledge, Information deficiencies, divergent interpretations).	**Risk** (Quality problems due to excessive pursuit of assembly rate, Potential costs increased due to uncertainties, Potential delays of manufacturers' limited capacity) **Industry Chain** (High cost due to discordant scale, Unintegrated industry chain, Insufficient construction capacity, Lack of well-developed technical systems, Lack of R&D input, Insufficient integrated design capacity, Low-level whole-decoration, Low-level of general contracting, Lack of industry team, Lack of practice and experience, Lack of new management method for prefabricated construction, Lack of synergetic information platform) **Social Climate and Public Opinion** (Lack of	**Market Demand** (Uncertainty of market demand, Difficulty of bidding price from contractors. Lack of awareness of prefabrication by the market and public) **Client Conservatism and Scepticism Lessons and Attitudinal Barriers Due to Historic Failures** **Durability of Prefabricated Unproven** **Industry Structure and Supply Chain** (Lack of practices and experiences from local projects. Fragmented industry structure. Lack of experienced collaboration groups. Lack of manufacturers and suppliers of prefabricated components. Dependence of traditional construction method. Lack of experienced contractors on prefabrication. Lack of experienced design consultancy and designers. Unable to modify design scheme)	**Contextual Factors** (e.g. economics conditions such as business demand, opportunities, uncertainty, competition and technology development, government involvement, regulation and rules, sustainability feature and stakeholders participation such as partnerships and attitudes)	**Lack of customer-focused and process-based performance measurement systems** (There is an industry tendency to measure performance in terms of time, cost and meeting code; but very limited consideration has been subjected to client satisfaction. These are not appropriate for continuous improvement because they are not effective in identifying the root-causes of quality and productivity losses. Financial measures and result-oriented performance indicators are backward focused and not measured until project is complete and so not responsive in delivering value). **Procurement and contracts** (Traditional Procurement methods and contracts may undermine the application of lean principles by creating adversarial relationships. This can ass waste to the process. Contract forms that allow one party to impose power over another create adversarial relations. These adversarial relations create transaction costs which are considered waste, and are thus opposing to the lean philosophy. Procurement form that tends to delegate design work to external designers, without any follow-up or incorporation, separates the design from the construction process and therefore misses the lean aim of collaboration and integration.

		Lack of Flexibility and Customisation (In the construction industry, in which every project is different and almost every client is different as well, there is less certainty that the investments made to implement robotic systems can be exploited in future projects with different clients).		comprehensive understanding of prefabricated construction, Lack of relative policies, laws and standards, Market disapproval, Lack of governmental incentives)			
Policy, Regulation and Legal Barriers (low R&D budgets, limited testing, codes and standards, and innovation culture)		**R&D Challenges** (Low R&D Budgets in the Construction Industry. Narrow scope of R&D. Weak innovation culture and Complex implementation. Unproved effectiveness / immature technology. Technologies remain difficult to use. Unavailable technology. Difficulty of new actors entering the market)			**Policies and Regulations** (Lack of technologies and testing institute to prefabricated components. Lack of local R&D institutes and services. Monotony of structure type. Reluctance to innovation and driven) **Technological Innovation** (Legal issues. Lack of design codes and standards for prefabricated components. Lack of governmental regulations and incentives)		
Organisational Innovation Strategy, Collaboration and Process Barriers (Workforce and fragmented subcontracting challenges, upskilling and training, averse change, communication and innovation culture, client, technology and site complexity, lack of standard process)	**Managerial Barriers** (integrated project delivery of offsite construction include unfamiliarity of workers to the practical innovations and technologies involved)	**Workforce Challenges and Untrained Workforce** (Skill gaps in construction workers have been identified as potential barriers. In this regard, the structure of the construction labour markets can also be a barrier for upskilling and that employers should engage actively to support skills development. Another factor is the current work culture/aversion to change, which highlights the effects of the weak innovation culture prevalent in the construction industry). Lack of continuous training, ageing and unskilled workforce. Not accepted by workers trade unions)	**Complexity** (Client changes, Changing site layouts, Lack of time and resources, Difficulty to measure improvements, Project uncertainty, Piece work contract, Technology issues, Lack of standard processes, Interdependency, Dynamic projects, Local variations)		**Potential unemployment issues to workers Organizational Mechanism and Culture**	**Structural factors** (e.g. Project condition such as risks, procurement setup such as costs, client outcome, resources and supply chain, management approach (e.g. process, planning, goals, strategy and leadership), communication process (formal and informal) and decision-making style)	**Fragmentation and Subcontracting** (Incentive for project supply chain partners to participants to cooperate and learn together. Participants have different circumstances and priorities. Limited number of partnering and integrated team-working projects. Poor communication has a negative impact on the effectiveness of the project delivery and coordination system. Contractors traditionally hire subcontractors and may have insufficient budgets and scope to participate effectively. **Lack of top management commitment and support** (Support from top management to provide sufficient time and resources to develop an effective plan, and manage changes arising from the implementation process. Other issues include poor

							planning, lack of delegation to enhance work flow, poor understanding of customer needs, lack of a participative management style for the workforce, logistics' problems, absence of look-ahead planning and poor coordination **Lack of adequate lean awareness/ understanding** (Lean thinking principles have not customised for construction. Some lean production measures may not be equally applicable. Requirement for a transformation in thinking, collaboration, flexibility, commitment, discipline, and a broad system-wide focus. **Educational issues** (Awareness by researchers, academics, practitioners and professional bodies in the UK. Some of these barriers include: lack of technical skills, ignorance to human resource management and development, inadequate training, poor understanding and awareness, poor team-work skills, illiteracy and computer illiteracy)
Economics and Finance Barriers (cost to adopt robotics, high initial capital investment, small scale of majority of companies, few resources for product testing, lowest price procurement, high training cost for advanced skills acquisition, economies of scale)	**Cost Barriers** (cost changes caused by implementing prefabrication)	**Contractor-side Economic Factors** (increased costs that construction companies must incur to adopt robotics in construction e.g. High initial capital investment and No strong need to improve productivity. The high cost of adopting solutions that replace manual labour are well known from other sectors, and its influence on adoption is evident. In a sector where the majority of the companies are small subcontractors and where only a few big construction companies can assign resources to test new technologies, high capital investments represent a major challenge) **Client-side Economic Factors** (The cost that the client must incur for adopting robotics. Decreasing public infra-structure budgets. Current public tendering practice that prioritises "lowest price" as the most important criterion to award projects represents a big limitation to innovation. In a highly competitive market, innovation spending is constrained)		**Cost** (high initial cost, High employee training cost, Higher average cost compared to traditional building)	**Cost** (High cost pressure without economics scale effect. High initial cost)		**Financial issues** (Funding is required to provide relevant tools and equipment, sufficient professional wages, incentives and reward systems; investment in training and development programmes, and perhaps employing a lean specialist to provide guidance to both employers and employees during the initial implementation. Issues include inadequate funding of projects, unstable markets for construction, lack of incentives and motivation, low professional remuneration, unwillingness of some companies to invest extra funds to provide training for their workers more than the essential legislation requirement)
Technical Technology Barriers (unproven /		**Technical and Work-culture Factors** (Unproved effectiveness/immature technology, highlights the concerns from industry stakeholders regarding the readiness of robotics			**Longer Lead-in Time During Design Stage Monopoly of Techniques**		**Adherence to traditional management concepts due to time and commercial pressure** (Application of traditional

immature technologies, worker alongside robotics safety, high task complexity and lack of standardisation and separation of design and construction)		to be used in construction. The high complexity of construction tasks that limits the usability and effectiveness of robotic and automated solutions. Human-robot interaction is also a significant challenge for robotics adoption in general. Lack of studies and theoretical models to predict and explain the perceived safety of construction workers working alongside robots. A testing environment using a virtual reality system. Aversion of workers to performing tasks alongside robots and that strictly defined physical areas for robot and human task can be beneficial). **High Task Complexity and Lack of Standardisation** (Design challenges such as low modularisation, reusability of solutions and information technology, immature functional integration, ineffective algorithms, robot intelligence, uncontrolled environment)			**Difficulty in Storing Prefabricated Elements** **Lack of Experienced Technicians of Assembly Onsite**		management concepts as opposed to productivity and quality initiatives. Commercial pressure to do the deal takes place over production issues. Wait for a crisis to make efforts to change; because it would be then too late to learn new skills and ways of thinking. **Design/ construction dichotomy** (Separation into two phases and creates lots of waste such as: incomplete and inaccurate designs, rework in design and construction, lack of buildable designs, final products with significant variation from values specified in the design, and disruption to contractors due to design changes made by designers.
Data Barriers							
Culture and Management Barriers (Aversion to change, culture, job security, communication, trust and risk, material and workflow planning, integration and collaboration across fragmented subcontractors)		**Cultural Challenges** (Aversion to change, very established industry, job security and robot-human interaction)	**Material Flow Issues** (Delivery reliability, Goods reception issues, Transporter issues, Builders' merchants issues, Flow and Inventories) **Internal Communication** (Lack of workflow planning, Attitude, Lack of trust, Unfamiliar with the project, Lack of sharing knowledge, Lack of updating plans, Not understanding the construction process, Information deficiencies, Lack of design phase integration, Not considering production rate		**Transportation of Prefabricated Elements and Access to the Building Site**	**Behavioural factors** (e.g. experience such as success/failure experience, learning, justification and cognitive choices, awareness and attitude (e.g. values, support and culture))	**Culture and human attitudinal issues** (The adversarial and transactional culture of the UK construction industry which prone to conflict and resistant to change. Lack of commitment, Lack of ability to work in group, lack of self-criticism, weak communication and transparency among teams of the production process, cultural issues in getting the subcontractors and workers to adopt the methodology in a comprehensive way, fear of taking risk, wrong attitude to change, not viewing housekeeping as a continuous effort, lack of team spirit among professionals, over-enthusiastic champions, dependency, lack of incentives and motivation, lack of trust, and fear of blame and contractual disputes.

			and receptiveness)				

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Jiang, L., Li, Z., Li, L. and Gao, Y., 2018. Constraints on the promotion of prefabricated construction in China. *Sustainability*, *10*(7), p.2516.

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Sarhan, S. and Fox, A., 2013. Barriers to implementing lean construction in the UK construction industry. *The Built & Human Environment Review*, 6(1), (1-17).

AlManei, M., Salonitis, K. and Xu, Y., 2017. Lean implementation frameworks: the challenges for SMEs.

Barriers to modularisation, component standardisation, kit of parts innovation

Search returned no references that aligned with the studies aim

Barriers to optimising machinery, plant reduction or plant efficiency innovation

Search returned no references that aligned with the studies aim

Barriers to Digital Construction / Smart Sites (drones, computer numerical control, 3D printing or automation innovation and augmented reality)

Author	Title	Channel	Aim	Notes	Status

Harrison (2015)	Small Innovative Company Growth: Barriers, Best Practices and Big Ideas	Article	**Learn lessons from 3D printing companies to understand their growth, barriers and practices**	Limited definition of the specific barriers	Grade B
Chen (2018)	Construction automation: Research areas, industry concerns and suggestions for advancement	Article	Investigates the possible benefits and challenges of construction Automation through a text-mining approach to the literature review	Limited definition of the specific barriers	Grade B
Zheng (2018)	Smart manufacturing systems for Industry 4.0	Article	This study examines smart manufacturing systems for Industry 4.0. It provide a conceptual framework and developed scenarios that pertain to smart design, smart machining, smart control, smart monitoring, and smart scheduling.	Limited definition of the specific barriers	**Grade C**
Le (2018)	Present focuses and future directions of decision-making in construction supply chain management: a systematic review	Article	This paper utilizes a systematic literature review methodology to identify the present focuses and discuss the future directions of decision-making in construction supply chain management (CSCM).	Limited definition of the specific barriers	Discard
Tezel et al (2017)	From Construction to Production: Enablers, Barriers and Opportunities for the Highways Supply Chain	Report	Aims at understanding enablers, barriers and opportunities to transform the current highways construction supply chain into a more manufacturing-like environment, where the benefits of production thinking can be achieved. The focus of the project is mostly on the adoption of off-site/modular (O/M) construction systems and advanced technologies.	Practical expression of the barriers	Grade B
Nimmy et al (2018)	Literature review on supply chain collaboration: comparison of various collaborative techniques	Article	The purpose of this paper is to create an understanding on the magnitude and dimension of supply chain collaboration (SCC) reported in the literature. The detailed review discusses various indicators that help companies to implement collaboration successfully and create awareness on the barriers faced while initiating collaboration in supply chain (SC).	Limited expression of the barriers	Discard
Soosay (2015)	A decade of supply chain collaboration and directions for future research	Article	This paper aims to conduct a systematic review of the literature on supply chain collaboration published over a 10-year period from 2005 to 2014. It explores the nature and extent of research undertaken to identify key themes emerging in the field and gaps that need to be addressed.	Limited expression of the barriers	Discard
Hussien (2017)	A Conceptual Framework Combining Augmented Reality with Agile Philosophy for the UK Construction Industry	PhD thesis	To develop a conceptual agile project management approach with augmented reality that can increase collaboration, communication, information sharing, and decision-making process, leading to reduced cost, time, waste, and creating better project output.	Limited definition of the specific barriers	Discard
Rauschnabel (2018)	Antecedents to the adoption of augmented reality smart glasses	Article	Develop and empirically test a theoretical model to assess the usage of augmented reality smart glasses	Focus on social and emotional barriers	Grade C
Edirisinghe, (2019)	Digital skin of the construction site	Article	The purpose of this paper is to explore and define the concept of the digital skin of the future smart construction site.	Highly descriptive and well visualised account of the challenges	Grade A

The following table provides a detailed description of literature-specific barriers for selected key references.

Barriers to drones, computer numerical control, 3D printing, automation and AR	**Chen (2018) Construction automation**	**Harrison (2015) 3D Printing**	**Zheng (2018) Industry 4.0**	**Parliament, House of Commons (2019)**	**Edirisinghe (2019) Digital skin**	**Rauschnabel (2018) Augmented reality smart glasses**	**Hussien (2017) Augmented reality**	**Tezel et al (2017) Manufacturing Offsite / Modular**
Ecosystem and Market Barriers (Cost of technology and low profit margins of the industry, gaps in R&D investment, shortage of	**Cost of Internet of Things and Smart Technologies** (low profit margins and market	**Market Barriers** (Cost of 3D printing / Additive Manufacturing systems and materials. there have been gaps in R&D investment	**Market Barriers** (Information confidentiality and security of data, Data transmission		**Ecosystem of the construction Industry** (Heterogeneity of construction sites and projects and diversity of stakeholder groups from various disciplines. Temporary project-based and transactional approach with few long-term working relationships	**Artificial Environment** (threatening other people's privacy, untrue, socially desirable or artificial	**Fragmentation and subcontracting Procurement and contracts Design / construction contrast**	**Design Barriers** (Traditional design mind-set, Constructors and manufacturers late involvement in design, Lack of DfMA product testing mentality, Constructability issues, Lack of a system design perspective, Lack of design standardisation,

technology-capable engineers, security of data)	position, additional innovation risks, costs associated in the protection of IP, academic collaboration and start-up costs)	and lack of capital, the market need is only partially developed, there is a shortage of talented engineers and difficulties in commercialising, high set up cost)	and service availability)		beyond the scope of a single project)	behaviour and conversation, could become a barrier to communication)	**Process problems within the organisation legal issues**	Over designing that does not allow for innovation, Insufficient interface design between existing components, Excessive reliance on design software.
Policy, Regulation and Legal Barriers (Cost and time of licensing drones and computer-user interface restrictions)				**Regulation of Use Barriers** (cost and time of licence by the Civil Aviation Authority. Restriction on where and how drones are used in construction (e.g. location to people and aircraft, etc)				
Organisational Innovation Strategy, Collaboration and Process Barriers (Fragmented solution finding, limited integration and learning and weaknesses in data storage and processing)			**Technical Manufacturing Barriers** (Fragmented and discreet manufacturing solutions are being developed with limited integration and learning, Advanced decision making, data storage and processing data and real-time data volume)		**Technology generalisability / applicability to any site** (Scalability and the ability for the system to grow. Communication protocols, timing for communication cycles, network reliability, packet loss and resilience)			**Construction Barriers** (Challenges in logistics, Insufficient management of supplier interfaces, Poorly planned temporary works, Poorly planned lifting operations, Over modularisation tightens tolerances and leaves no room for site arrangements, Quality control challenges with manufacturers, Supply chain coordination issues, Rigid and descriptive material approval processes, Ad-hoc idea capturing for O/M systems, High risk aversion for on-site automation and robotics. **Decision Making** (Lack of catalogue of available systems, Ad-hoc decision making by a few people, Difficult to perform collaborative value engineering, Cost is the dominant factor in decision making) **Project Governance** (Lack of clear DfMA approach, Many points of contact for different systems, Insufficient know-how sharing in the supply chain, Client expectations and priorities are not clear for the supply

								chain, Lack of objective evaluation (excessive positive bias)
Economics and Finance Barriers					**Economic challenges** (Cost of equipment to be a barrier to technology adoption in the industry and beyond laboratory experiments).		**Time and commercial pressure Financial issues High cost of the software and its implementation Licence problems**	**Commercial** (Insufficient preferred supplier / manufacturers lists to enable earlier involvement, Lack of coherent work packages that allow O/M (ownership issues, Short term relationships with suppliers)
Technical Technology Barriers (robots-automation know-how, lack of research, maturity of information management, speed of manufacture and diversity in batch size, materials limits)	**Technical Manufacturing Barriers** (Lack of knowledge on the link between construction robots and automation systems. A lack of maturity of use of information, lack of research on how to combine computer aided design with onsite robotic and automation systems).	**Technical Manufacturing Constraints** (Repeatability and consistency between different systems and batches. Speed of 3D printing / Additive Manufacturing systems. Lack of materials, materials development and applications. The build platform is also relatively small limiting the size of products produced).			**Technology availability, diffusion, observability, trial-ability, compatibility and interoperability** (Gaps in research on emerging areas (safety, BIM, AR), as well as a lack of adoption of mature technologies, such as RFIDs and other tracking technologies. Government funding and market forces barriers. Lack of standards) **Technology Robustness Limitations of hardware/sensors and software/applications** (e.g. low reliability, low computational power and limited battery life of sensors and devices and the sensitivity of sensors and the accuracy of sensor data significantly affect the reliable functioning). **Standardisation of technologies** (Standardisation of RFIDs in the construction industry. Common regulations and policies. Open standards should be agreed upon and used by all stakeholders. Specifying unique identifiers for objects, such as construction ID cards and PPE items. Standardisation of tools and data sets. Benchmarking and control. Testing of new products, processes, systems and solutions, from early stage ideas to commercial launches - test-beds, if widely accessible, can			**Technical Barriers** (Inoperability issues, Insufficient component libraries, Suppliers lagging in BIM capabilities, BIM seen as technology solution with no consideration of stakeholder/process integration, Difficult to quantify financial impact)

					foster rapid standardisation across the sector. **Technology acceptance and up-skilling** (very few studies have evaluated the technologies from the social and human perspective, lack of users involvement in the technology development process. User requirement analysis, knowledge and ability of organisation to adapt and improve upon current processes by adopting new technology. Technology up-skilling - particularly among sub-contractors)			
Data Barriers (Required change in business and reporting models within the industry, integration challenges)				**Scale of Digital Data Barriers** (Required change in business and reporting models within the industry. Challenges associated with the integration of as-built data systems (such as laser scanned measurements from inside a building alongside drone data from external areas) and the influence this will have on existing 2D job roles.		**Ethical Fears, Negative Perceptions and Norms** (while the legal fears associated with what is or not permissible, there are concerns over personal privacy) **Legitimacy in the Usage Context** (In the workplace, supervisors and co-workers might observe one other, cameras might survey the work-space or work behaviour is tracked regardless. In another context operatives may be talking about personal issues)	**Lack of national standards Data structure and data interoperability limits of the integration of BIM**	
Culture and Management Barriers							**Lack of adequate Lean awareness and understanding**	

							Client roles and responsibility **Lack of customer-focused and process-based performance measurement system** **Culture and human attitudinal issues** **Lack of top management commitment** **Lack of skilled professionals** **Educational issues**	

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Barriers to Digital FM / Digital Twin (smart assets and digital FM, sensors, BIM FM, locational GIS, remote sensing or internet of things innovation)

Author	Title	Channel	Aim	Notes	Status
Ivson (2019)	A Systematic Review of Visualization in Building Information Modeling	Article	The goal of this article is to encourage visualization researchers to increase their involvement with BIM.	Limited focus	Discard
Terreno (2019)	Synergies between Lean Concepts and BIM in FM	Article	To study the implementation of BIM in Facilities Management (FM) .	Many barriers identified	Grade A
Volk (2014)	Building Information Modeling (BIM) for existing buildings	Article	To review literature on using BIM for existing buildings.	Not directly relevant	Grade B

The following table provides a detailed description of literature-specific barriers for selected key references.

Barriers to smart assets and digital twin, sensors, BIM FM, locational GIS, remote sensing or internet of things innovation	**Terreno (2019) BIM in FM**	**Volk (2014) BIM in FM**	**Lydon et al (2019) Digital Twin**
Ecosystem and Market Barriers (Variety of measures, scale of application, accessibility to commercial software and open sourcing of code)		**Varying quality assessments of BIM models**	**Cost of Software and Expert User Time Barriers** (The use of application scripting and automated analysis process to create a multifunctional building element) **Commercial Software and Open Source Code** (Cost and IP is a barrier to adaption of high-resolution methods, open source tools and solvers. The replacement of a commercial code with a suitable open source code and scripting languages (e.g. Python with extension libraries such as Pandas for data structures and Seaborn for data visualisation).
Policy, Regulation and Legal Barriers (lack of clear regulation, standards and codes)			**High-resolution Modelling Barriers** (The requirement for extensive expert user setup time. While many commercial codes provide methods of automation, these solutions are dependent on the commercial code and can have limitations depending on the user case).
Organisational Innovation Strategy, Collaboration and Process Barriers (ambiguity of requirements, communication gaps, errors and fragmented planning and workflow)	**Ambiguity of requirements** (when requirements are not clearly spelt out, the resulting submittals can include unnecessary or excessive information, bloating the data inventory with irrelevant and possibly defective information. Extra effort will be required to audit and correct the information, with personnel searching for the right information resulting in work distractions) **Communication gaps** (gaps in effective and timely communication between teams and individuals within an FM organization can be costly. The resulting wastes lead to excessive detail or unnecessary information/functionality within the process, increased need for revisions and excessive preventative maintenance)		**Current Planner Workflows for Constructing Buildings** (This process is typically fragmented and sequential, which makes it very difficult to focus on adaptable high performance outcomes)
Economics and Finance Barriers			

Technical Technology Barriers (Integration of BIM translation, transition and operation, weaknesses in data maintenance)	**Barriers to BIM in translation** (the conversion of drawings and information for existing buildings to a 3D intelligent database format (e.g. Data collection, field verification, modelling, audit) **Barriers to BIM in transition** (the phase of information handover from the project team to the facilities team (e.g. Submittals, validation, editing, upload) **Technology barriers** (interoperability of data to prevent rework, software and hardware reliability, technology and information integration, data error, security and loss, poor model maintenance culture) **Barriers to BIM in operations** - BIM-enabled activities performed by the facilities management team in the management of their building portfolio (Job planning, information, gathering, location finding, preparation)	**Underdeveloped object properties and processes for maintenance and especially deconstruction purposes.** **Update and maintenance of information in BIM** **Handling and modelling of uncertain data, objects and relations occurring in existing buildings in BIM** **Challenges of capturing structural, concealed or semantic building information under changing environmental conditions**	
Data Barriers (Data quality, interoperability and automation)	**Data Quality Barriers** (Inconsistent naming, formatting and storage of data, Insufficient or overwhelming volumes of data, Unreliable data needing validation due to errors or obsolescence, Incomplete or obscured information, Unavailable information and Irrelevant information)	**Interoperability between BIM models of different generations** **The automation of data capture and BIM creation (without pre-existing BIM)** **Transforming captured data into unambiguous semantic BIM objects and relationships.**	
Culture and Management Barriers (Training, expertise, collaboration and open information sharing)	**Lack of training/poor expertise in 3D modelling/mobile technologies**—When FM personnel are poorly trained and not properly equipped for the use of BIM data, excess man hours are wasted in production. Overproduction and excess inventory are all possibilities, with extra processing of data requiring excessive iterations or verification and a lot of rework and re-handling. Unnecessary movement of workers are to be expected, along with idle time from delays in receiving information, and data with defective quality. **Organizational culture lacking collaboration and open information sharing in FM organizations**—similar to communication gaps in organizations, a poor culture of collaboration or information sharing results in redundant development of information, which is partly responsible for obsolete information owing to poor management/coordination.		

The references include the following:

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