Chapter 3
Digitally-Enabled Design Management

Emma Tallet
Northumbria University, UK

Barry Gledson
Northumbria University, UK

Kay Rogage
Northumbria University, UK

Anna Thompson
Turner & Townsend, UK

Drew Wiggett
Turner & Townsend, UK

ABSTRACT

Calls for the digital transformation of the construction sector in part revolve around a need for productivity improvements, with a focus upon project time and cost enhancements. The purpose of this work is to provide a state-of-the-art analysis of design management (DM) usually employed to oversee design quality by coordinating design information, typically on behalf of a construction contractor. DM methods, activities, and processes with respect to the potential and underutilisation of building information modelling (BIM) are discussed. A synthesis of recent research efforts is provided identifying further emerging, disruptive, but underutilised digital tools and technologies, which when integrated with BIM, are capable of supporting DM processes. This chapter will aid practitioners and researchers in the design, implementation, and management of digital tools, and provide greater support to the DM function on modern construction projects. It will also be of use to students for a grounding in BIM and BIM-related technologies.

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INTRODUCTION

In this chapter, a review of the Design Management (DM) literature is provided, alongside a review of recent research efforts into technology to support DM processes and collaborative working. The chapter provides insight into technologies including Virtual Reality (VR), Point Cloud (PC), blockchain and Artificial Intelligence (AI), which form part of the construction digital transformation landscape. The implementation of these technologies and their application for improving productivity, efficiency and quality outcomes are analysed. The chapter also highlights how technological developments can be integrated with BIM.

The authors discuss BIM, its central role in project delivery and how it is being used to build capacity to deliver outcomes in the construction sector. The authors consider the DM literature, covering the activities and processes of the discipline and further the role of BIM in supporting DM. In the Technology section, the authors discuss recent research and development in BIM and technology to support DM processes. This is followed by a review of technology products available commercially. The authors conclude with some recommendations for the adoption and use of technology for BIM and DM.

BACKGROUND

This section discusses the integration of BIM and DM for Digitally-Enabled Design Management. The authors begin discussing the DM discipline before introducing the reader to BIM and providing a discussion on BIM implementation. This is followed by an introduction to IPD and a discussion on the relationship between BIM and DM.

Design Management

DM is an existing and evolving discipline which emerged due to higher use of design and build procurement methods, increasing contractor involvement in the design coordination process. A demand for DM has also emerged as construction processes, buildability and buildings have become more complex (Eynon, 2013).

In a construction project team, DM supports the related Project Management (PM) and Construction Management (CM) discipline. The PM covers budget and programme while the CM predominantly covers health and safety and site operations. DM overlaps with these roles but has its own principal foci of managing design information, providing buildability analysis, and looking at construction strategy, process and cost (Emmitt & Ruikar, 2013). DM consists of the management of *"activities, people, processes and resources"* (Eynon, 2013, p.2), requiring effective problem solving and communication skills; understood as 'soft skills' (Emmitt & Ruikar, 2013; Tvedt et al., 2019) to ensure information flow and efficiency/value in project delivery in line with specified requirements of cost, time and quality (Eynon, 2013).

DM activities (see Emmitt & Ruikar, 2013 and Emmitt, 2016) operate at strategic organisational and project levels and include management, processes, collaboration, coordination and the integration of design and construction disciplines (Emmitt & Ruikar, 2013; Eynon, 2013). DM activities typically consist of (from Emmitt & Ruikar, 2013, p.65):

- **Design Review:** Pre-construction and construction stage review of design information.
- **Coordination:** Coordination of consultants' design information ensuring flow of information.
- **Tendering:** Managing pre-construction tenders and bids.
- **Design Changes:** Managing design changes, including approval.
- **Requests for Information (RFIs):** Managing and submitting RFIs.
- **Buildability:** Analysing design information to determine buildability and construction process. Considerations include coordination of disciplines and trades, site organisation, health and safety, and efficiencies such as cost.
- **Value Management:** Value-adding value engineering and innovation.
- **Cost Management:** Managing and monitoring the cost of design and construction.

Effective DM relies on lean principles (see Emmitt, 2010, p.163) and management methods to identify buildability problems in design information prior to the commencement of construction. Design changes during the construction process can lead to costs and delays. Ensuring the design is correct before construction progresses reduces the risks associated with uncertainty. The design phase is an opportunity to eliminate waste in the construction phase and create value (Emmitt & Ruikar, 2013).

The communication and understanding fostered by construction site meetings can be effective in achieving lean principles for information flow. The project team is temporary, multi-disciplinary, and in constant change. Integrating the project participants requires good management from the outset (Emmitt, 2010).

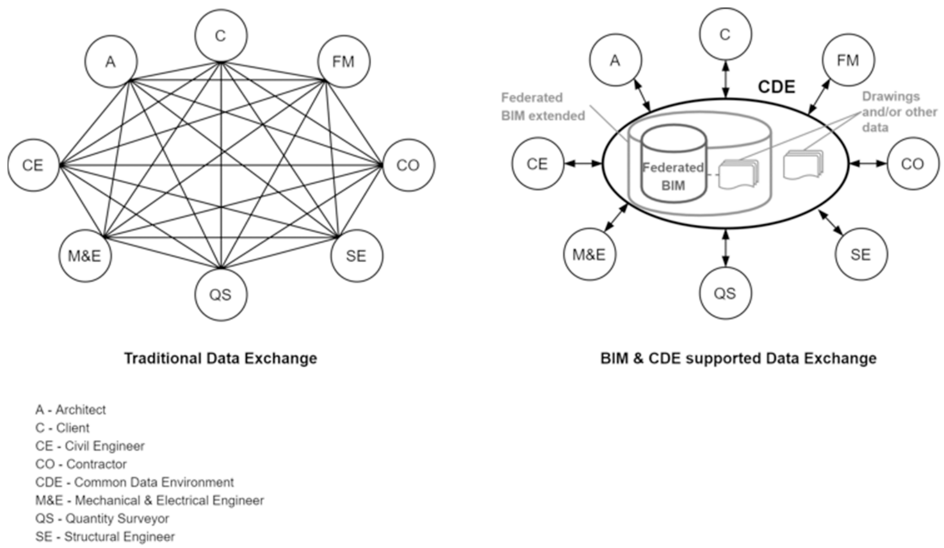
Building Information Modelling (BIM)

The UK Government has established BIM as best practice (HM Government, March 2016) and BIM has been mandatory on government projects as of 2016 (Hackett & Statham, 2016).

A BIM is defined as a computerised entity which structures and holds information as a representation of a designed or physical asset, forming a basis for decision making (Antwi-Afari et al., 2018; Emmitt & Ruikar, 2013; Hackett & Stratham, 2016; ISO 19650-1:2018). A central BIM is a more effective way of managing data, supporting drawing creation from a single information source; this eliminates a key source of errors (Sacks, et al., 2018) and supports greater building complexity. A BIM is parametric (Azhar et al., 2012) as modelled components are enriched with intelligent data (Emmitt & Ruikar, 2013; Hackett & Stratham, 2016). Moreover, it is possible to extend BIM beyond 3D to include time and cost dimensions and more (Emmitt & Ruikar, 2013).

BIM is central to a collaborative way of working (Antwi-Afari et al., 2018; Emmitt & Ruikar, 2013; ISO 19650-1:2018). ISO 19650-1:2018 stipulates the use of a central Common Data Environment (CDE) to support collaboration, where federated BIMs are shared throughout production phases (Fig. 1) (ISO 19650-1:2018; Merschbrok & Munkvold, 2015). ISO 19650-1:2018 further sets out a structure and framework for the workflow of data transfer and recommends that each project participant or organisation is responsible for their own information container or BIM (ISO 19650-1:2018). It follows that BIM is defined as a process for the integration of the project team and for the collaborative processing and management of design and construction information (Fig. 1) (Azhar et al., 2012; Piroozfar et al., 2019). When implemented using recommended processes listed in best practice guidance and/or official standards, BIM has capacity to ensure accurate, complete, consistent, well managed and high-quality information is efficiently put together and accessible to the right people at the right time (Hackett & Stratham, 2016; ISO 19650-1:2018).

Figure 1. Traditional information exchange vs information exchange with a central repository/database/ CDE
Source: adapted from Chen (2005, Fig. 1) and Azhar et al. (2012, Fig. 2)



BIM as a process has the capability to reduce costs and add value to project outcomes (ISO 19650-1:2018; Arayici et al., 2010 cited in Koseoglu & Nurtan-Gunes, 2018), with studies suggesting the implementation of BIM has outcomes in productivity, collaboration and relationships (Antwi-Afari et al., 2018; Azhar et al., 2008; Chong et al., 2014; Koseoglu & Nurtan-Gunes, 2018). BIM implementation can ensure information is consistent, coordinated and standardised across the project team (Hackett & Stratham, 2016).

BIM Implementation and Systems Design

BIM is a disruptive innovation, requiring transformative change to working practices and processes (Gledson, 2016). People, management and processes are key in technology implementation, with high-level management and strategy required (Emmitt & Ruikar, 2013; Gledson, 2016; Hackett & Stratham, 2016). BIM can be affected by DM outcomes collaboration, coordination, planning and 3D visualisation among others and vice versa, creating a dual direction relationship between BIM and DM (Antwi-Afari et al., 2018). ISO 19650-1:2018 requires that BIM implementation is managed from the project outset (ISO 19650-1:2018; Piroozfar et al., 2019) in line with the IPD approach (Azhar et al., 2012), and that BIM is integrated with information management processes as one and the same (ISO 19650-1:2018).

Construction is slow to adopt disruptive approaches (Farmer, 2016; Koseoglu & Nurtan-Gunes, 2018) with companies underutilising BIM (Koseoglu & Nurtan-Gunes, 2018; Merschbrok & Munkvold, 2015). Where confidence in BIM is lacking, traditional working processes are maintained alongside new BIM workflows. This duplication can lead to inefficiencies and potential for error. Benefits of BIM can include improved visualisation, design coordination, clash detection and collaboration. However, conflict can exist between users' technological capability and issues around the standard of digital tools, particularly in older and experienced workers who may expect structure and completeness (Gledson, 2016). Innovations such as BIM are continuously developing, particularly as industry moves into its 4th revolution (Alaloul et al., 2020). For example, instead of relying on drawings as the verified source of design information, the objective is to have all design information contained in a BIM. Currently a BIM may only consist of main components, and may not include detailing (Sacks et al., 2018). Although research into measuring BIM benefits and value is ongoing (Abdirad, 2017), studies show BIM achieves outcomes in productivity (Azhar et al., April 2008; Azhar et al., 2011; Poirier et al., 2015). Despite evidence of BIM's value, construction shows a lag between the implementation of digital tools and the availability of those tools. In order to bring its performance in line with other sectors, construction should look to exploit digitalisation (Alaloul et al., 2020).

Construction is not exploiting the digital tools available (Alaloul et al., 2020). BIM implementation requires process, strategy and management (Emmitt & Ruikar, 2013; Gledson, 2016) with collaboration (Antwi-Afari et al., 2018; Emmitt & Ruikar, 2013; ISO 19650-1:2018) and information management at its centre (ISO 19650-1:2018).

BIM & Project Delivery

Traditional modes of procurement and competitive tendering can create waste and contribute toward project-related failure (Boukendour and Hughes, 2014 cited in Uusitalo et al., 2019). Farmer recommends fundamental change to the way project are managed and procured. Fixed and defensive contracts make it difficult to organise and integrate project participants leading to broken up processes and low levels of trust (Oct, 2016), which damage the team's ability to solve problems (Boukendour and Hughes, 2014 cited in Uusitalo et al., 2019). Collaboration requires contributions are treated equally; and as participants are not managed under the same organisation, DM focuses on the quality of participants' relationships or interfaces as sources of value (Emmitt, 2010; Emmitt & Ruikar, 2013), with trust identified as important for problem solving (Uusitalo et al., 2019).

The UK Government has identified collaborative procurement and early involvement of the contractor and supply chain in design as important in attaining efficiencies (HM Government, March 2016). Latham's reports *'Trust and Money'* (1993) and *'Constructing the Team'* (1994) addressed the culture of fragmentation and conflict in construction for greater collaboration and integration in project delivery to deliver value. This literature was later built on by Egan with *'Rethinking Construction'* (1998) and *'Accelerating Change'* (2002) (cited in Emmitt & Ruikar, 2013) Evidence for the success of collaborative procurement can be measured on a project-by-project basis (Bowles and Morgan, 2016; HM Government, July 2014), with the government establishing evidence for best practice for their new forms of procurement (HM Government, March 2016).

The Integrated Project Delivery (IPD) approach consists of early stakeholder involvement for a well-planned design and construction which meets identified requirements. Early stakeholder involvement and organisation is also important in BIM management (Azhar et al., 2012); with IPD addressing and removing barriers to BIM adoption by ensuring collaboration and trust is in place from the start (Piroozfar et al., 2019). As BIM provides the means for collaboration and integration, BIM is a tool/

requirement for IPD. It follows that the two concepts and processes of IPD and BIM are synonymous (Fig. 2) (Piroozfar et al., 2019).

BIM & Design Management Methods

BIM can be integrated with DM activities, processes and methods (Emmitt & Ruikar, 2013). It is important DM follows a clear process or significant waste can occur through constant rework (Eynon, 2013). The high-level DM processes are set-out according to BS 7000-4:2013; and include the alignment of DM processes with BIM standards and processes. ISO 19650-1:2018 stipulates the management of design information through the use of BIM and a CDE. As federated information containers are shared and accessed via the CDE according to process (see ISO 19650-1:2018), integrating the project team (Fig. 1) (Emmitt & Ruikar, 2013; Piroozfar et al., 2019), outcomes can be achieved in DM principles of communication, collaboration, coordination and trust (Fig. 2) (Azhar et al., 2012; Piroozfar et al., 2019).

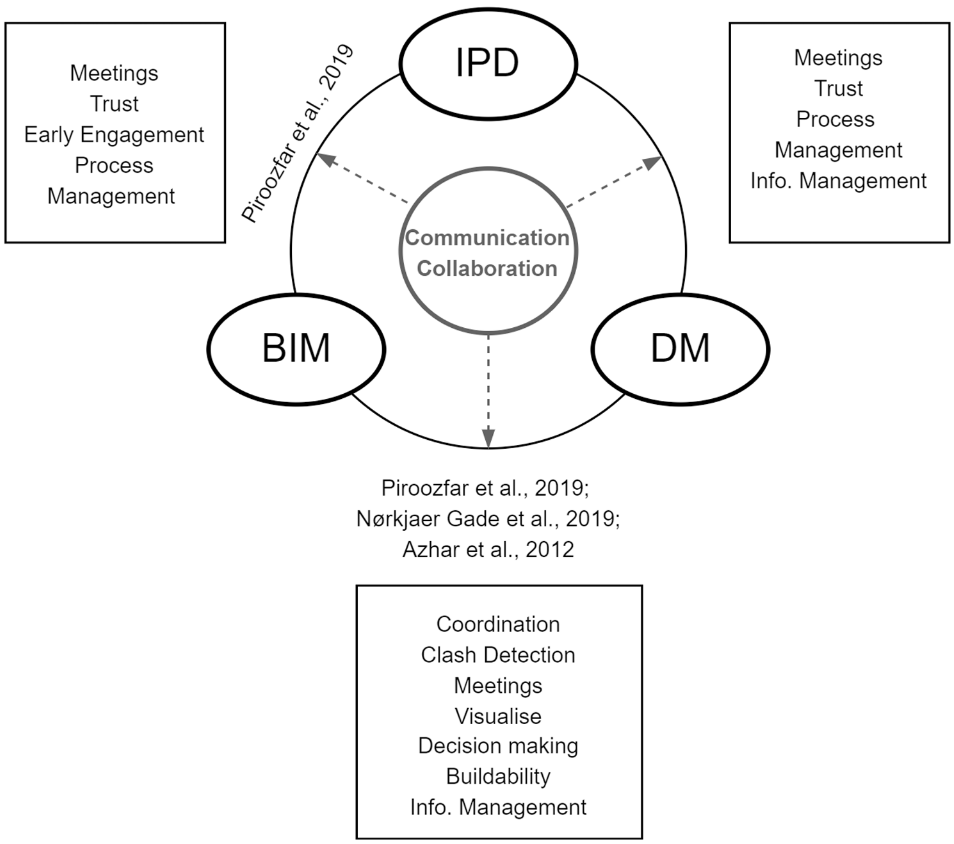
The application of technology has the capacity to handle processing requirements and to organise and structure design information (Hackett & Stratham, 2016; Koseoglu & Nurtan-Gunes, 2018; ISO 19650-1:2018) supporting complexity (Azhar et al., 2012). In managing building data in 3D, with the use of a centralised source (Sacks, et al., 2018), a BIM-based CDE workflow can have tools to enable design visualisation before construction. Moreover, BIM-enabled tools support coordination and clash detection at work package interfaces (Emmitt & Ruikar, 2013; Koseoglu & Nurtan-Gunes, 2018). Design visualisation is an important aid for communication, collaboration, coordination and thus design development (Emmitt & Ruikar, 2013; Hackett & Stratham, 2016) and can be a focal point for communication and collaborative problem solving among project participants in a synchronous setting (Nørkjaer Gade et al., 2019).

Communication is a relational skill (Hargie et al., 2006 cited in Tvedt et al., 2019) and is developed over time as more information and understanding is transferred (Emmitt, 2010; Uusitalo et al., 2019). In team building, it is important members have developed relationships based on mutual understanding (Tvedt et al., 2019), with research suggesting a link between communication and the success of construction projects (Knotten et al., 2017). As collaborative group decisions can be better than decisions made by individuals, the processes of decision making can be critical in the project team's ability to make decisions which add value to the project (Emmitt, 2010); with research further suggesting the quality of decision making is important in project success (Knotten et al., 2017).

Important in coordination, research suggests information flow is support by trust (Tvedt et al., 2019; Uusitalo et al., 2019) as trust and lean DM reciprocate one another (Uusitalo et al., 2019). Research suggests that trust can provide a foundation for team relationships by creating an environment for mutual understanding (Tvedt et al., 2019). Trust is based on good communication (Emmitt, 2010; Uusitalo et al., 2019) and is important in reducing conflict, increasing collaboration and improving team problem solving (Uusitalo et al., 2019). Generating trust is important in creating working conditions which foster creativity (Hoezen et al., 2006 cited in Ajayi et al., 2019; Edmondson 1999 cited in Uusitalo et al., 2019) and generate social capital (Coleman 1988 cited in Uusitalo et al., 2019) (Fig. 2).

The management framework provided by IPD has the potential to provide opportunities to the DM to reduce stress, resolve low-trust relationships, facilitate team integration and facilitate strong team relationships (Piroozfar et al., 2019), enabling a dual direction relationship between IPD and DM. Piroozfar et al., further finds that in establishing strong communication from a DM perspective, BIM adoption and a high trust working environments reinforce and reciprocate one another, further enabling a dual direction relationship between IPD and BIM (2019) and as such, a dual direction relationship between DM and BIM. According to Tvedt et al., it follows that the DM design process is a learning process and decision making process, digitalised or partially digitalised by BIM (2019) (Fig. 2).

Figure 2. Dual relationships between DM, IPD and BIM based on key concepts of communication and collaboration



However, there are limitations to BIM-based and other technology-based communication, particularly for remote teams. Despite optimism towards technology take-up, communication is only partly digitalised, and BIM is considered a tool for communication, rather than providing full support (Tvedt et al., 2019). Information sent over digital means is not always clear and understood and does not always reach its destination (Tvedt et al., 2019; Tauriainen et al., 2016 cited in Uusitalo et al., 2019) as understanding is often expressed in facial expression, body language and/or tone of voice (Mehrabian, 2007 cited in Emmitt, 2010; Friedman, 2019).

Communication is subjective, based on human experience and individual personality, with no clear process or standard (Tvedt et al., 2019). Even where business standard communication tools are used, such as video conferencing, these tools still fall short of face-to-face communication in the social presence required for processing social cues (Fox & McEwan, 2017). An overreliance on inappropriate or deficient digitalised communication is cited as a cause of DM failure (Tvedt et al., 2019; Tauriainen et al., 2016 cited in Uusitalo et al., 2019) and might negatively impact the design process. It is important digitalised communication is considered against requirements for relational human interaction (Tvedt et al., 2019).

Organised and structured meetings are an important team building opportunity. Team building can be facilitated by the DM (Tvedt et al., 2019) with research suggesting that a good use of meetings is related to project success (Gorse, 2002 cited in Emmitt & Ruikar, 2013). Meetings are critical in managing information flow and in organising the coordination of information to establish a 'value stream' according to lean principles. Information needs to be accessible and of high quality for efficiency on the construction site. Where information is poor or absent, site will have to request further information, production in construction may be poor, delayed, incorrect or defunct; or design changes may be required (Emmitt, 2010).

Despite best intentions towards collaborative processes, research suggests fragmented working practices can persist. Poor communication, leading to poor quality information and poor information flow, does not only impact on the success or failure of projects, but also causes significant workplace stress (Ajayi et al., 2019). Significant costs and losses in productivity and talent are associated with conflict (Malik & Lenka, 2019) and stress in the workplace (Stevenson & Farmer, 2017 cited in Ajayi et al., 2019), with construction having particularly poor reputation (Farmer, 2016; Monitor Deliotte, 2017 cited in Ajayi et al., 2019). Piroozfar et al. identified poor workplace culture, poor planning and moods as barriers to trust (2019); and as such, barriers to a productive design process (Tvedt et al., 2019) (Fig. 2), with conflict within project teams also identified as a barrier to successful and productive BIM adoption (Piroozfar et al., 2019).

Organisational factors interact with the characteristics of participants to predict destructive behaviour (Hackney & Perrewé, 2018, Malik & Lenka, 2019, see Fig 1; Samnani & Singh, 2016, see Fig. 1) as a phenomenon or process (Douglas et al., 2008 cited in Hackney & Perrewé, 2018). Interventions to destructive behaviours include individual resources, community and relationships, and establishment strategy, planning and communication (Malik & Lenka, 2019, see Fig. 1).

For example, disruption and obstacles to completing tasks can trigger stress and predict destructive behaviours. In line with the frustration-aggression model, work related stress can be displaced into other areas of functioning (Hackney & Perrewé, 2018). In the case of poor information flow, problems can be mitigated with realistic project planning, resource allocation and risk management, and improved team communication (Ajayi et al., 2019). Moreover, as moods such as anger can predict destructive behaviour (Hackney & Perrewé, 2018), the effective DM can influence these 'moods' to create an environment more inducive to learning and creativity (Long and Arroyo, 2018 cited in Tvedt et al., 2019).

IPD supports the DM in facilitating communication and collaboration early in the project team. In establishing strong communication from a DM perspective, BIM adoption and a high trust working environments reciprocate one another (Piroozfar et al., 2019), creating a dual direction between DM and BIM (Fig. 2). Ajayi et al. describe how BIM and IPD have the potential to break down communication barriers by providing increasingly sophisticated digital tools for communication, such as cloud-based federated models (Fig 1), providing information management capabilities which are quicker or potentially increasingly synchronous, reducing or eliminating stress related to information flow (2019).

It is important to facilitate and foster a high trust and well-resourced working environment (Ajayi et al., 2019; Malik & Lenka, 2019) for high-trust and productive workplaces (Hackney & Perrewé, 2018). Future research directions lie in investigating the causes of conflict in project team relationships, and how DMs can intervene and facilitate productive working relationships, creating value in the learning and design process (Tvedt et al., 2019). Further research is also required to investigate the role of BIM and BIM-based digital tools in supporting subjective human experience (Tvedt et al., 2019) when digitalising or partially digitalising DM processes of communication, collaboration and coordination.

Digital Design Management

There are a range of BIM-based technologies available on the market which offer the functionality with which to carry out DM processes (Emmitt & Ruikar, 2013). This section provides a state-of-the-art discussion on recent research and development in BIM and further technologies to support DM processes.

The discussion is broken down into 6 technology areas: collaboration and coordination tools, 4D/5D BIM, Virtual Reality (VR), Point Cloud (PC), Artificial Intelligence (AI) and blockchain. These technologies can be integrated with BIM, with Table 1 showing how each technology area can support DM task areas of: collaboration and coordination, optimisation, as-built validation, and security and trust.

Table 1. Matrix of technology to support DM task areas

	Collaboration Coordination Tools	**4D/5D BIM**	**Virtual Reality**	**Point Cloud**	**Artificial Intelligence**	**Blockchain**
Collaboration Coordination	✓	✓	✓	✓		✓
Optimisation	✓	✓	✓		✓	
Validation	✓			✓	✓	
Security & Trust	✓					✓

BIM-Based Communication & Collaboration

The CDE provides tools for the visualisation of the design (Koseoglu & Nurtan-Gunes, 2018) and has the potential to integrate participants at construction site meetings, supporting communication (Nørkjaer Gade, et al., 2019). The coordination process can be complex, and BIM offers a number of tools to reduce errors and improve efficiency. Digital tools such as Navisworks can partly automate the clash detection activity so that clashes are picked up and resolved before construction, while visual 3D BIMs can be utilised in construction site meetings to discuss coordination issues (Gledson, 2016; Mehrbod et al., 2019).

BIM and Coordination

Annotation, recording and visualisation tools support construction DM processes to resolve problems on the construction site (Mehrbod et al., 2019). The use of BIM for collaboration, coordination and clash detection is well established but adoption remains an issue, with participants often falling back to 2D paper-based methods in meetings (Chu et al., 2018; Mehrbod et al., 2019), leading to inefficiencies and errors (Mehrbod et al., 2019; Wang et al., 2014 cited in Chu et al., 2018). The usability of digital tools can be a barrier to effective use (Mehrbod et al., 2019), and the range of BIM tools and information formats can add to confusion when conducting DM tasks, especially when dealing with large volumes of information (Chu et al., 2018).

The CDE described by ISO 19650-1:2018 has been expanded and can include tools to aid more seamless information access for more efficient DM problem solving, aiding closer collaboration between design and construction professionals. The key tools include:

- **Common Data Environment (CDE):** A CDE is defined as an *"agreed source of information"* (ISO 19650-1:2018, p.5) and consists of a web-based cloud platform where BIMs and drawings can be uploaded.
- **Revision:** ISO 19650-1:2018 recommends the use of a status code and a revision code. The status code reflects the permitted use of the information: 'work-in-progress', 'shared' or 'published'. The design information submitted requires approval to pass through each stage (ISO 19650-1:2018). The revision code will maintain a record or thread of changes to the design information, as recommended by the Hackitt Review (May, 2018). As in ISO 19650-1:2018, this archive is retained should there be legal proceedings or lessons to learn at a later date.
- **Coordination:** Tools to support coordination tasks are as follows:
    - Web-based tools for viewing federated BIMs on a range of devices (Koseoglu & Nurtan-Gunes, 2018) can be essential for navigating the design information and understanding the information from different angles (Mehrbod et al., 2019).
    - Parametrically linking drawings to the 3D model for review if required can be important for, as in Mehrbod et al. (2019), the accessibility of design information. Transitioning between different items in work packages can be cumbersome and inefficient if not properly facilitated.
    - Tools for marking up coordination issues on the 3D model with functionality to attach further information such as a photo can be important (Koseoglu & Nurtan-Gunes, 2018). While sketching on 3D artifacts can be underutilised, annotation is a frequently used interaction when solving coordination issues or construction DM problems (Mehrbod et al., 2019) but can be utilised in communications and documentation (Han & Golparvar-Fard, 2017).
    - In-built and automated revisioning of design information complies with information management procedures, maintaining an archive as in ISO 19650-1:2018 and a 'thread' of information as recommended by the Hackitt Report (May 2018).
- **BIM Collaboration Format (BCF):** Many platforms have developed extended collaboration capabilities using the BIM Collaboration Format (BCF) (see Boton, 2018). These capabilities include:
    - The ability to export 3D mark-ups to BCF format (see Sacks et al., 2018), this format can be imported into Revit, Navisworks or Solibri among other applications for further investigation.
    - The ability to parametrically view a list of mark-ups on a model and assign tasks to individuals in the drawing office(s).
    - The ability to monitor the completion of tasks assigned, see Revizto at Vizerra SA, (2012-2020).
- **Authorisation/Permissions:** It can be important to provide authorisations/permissions so that each participant in the project team only access the information they require, especially where there is a requirement for compliance with ISO 19650-5:2020.

The process of solving a DM problem includes identification, solution building, and solution documentation (Mehrbod et al., 2015 cited in Mehrbod et al., 2019). Solving DM problems requires accessing design information to explain, present, analyse, query and visualise the problem; and document any decisions. However, further research is required around the coordination and the DM problem solving process (Mehrbod et al., 2019).

The tools within an extended CDE support DM activities of design review and coordination. However, communication tends to be supported during construction rather than at preconstruction design stage, meaning the coordination activities supported may be more reactive. The extended CDE tools do not support the design change process or the process of submitting RFIs. These processes are sped up, made informal, and may lack appropriate controls such as approval.

BIM and the Construction Site

Access to design information via a CDE ensures the most up-to-date information is being used and is accessible when required. The extended CDE enables a more seamless connection between the construction site and the design office (Koseoglu & Nurtan-Gunes, 2018). VR can be further applied to resolve interactivity issues (Mehrbod et al., 2019). Mobile devices can be utilised on the construction site as part of lean project delivery to view models and drawings, resolve coordination and DM problems (Koseoglu & Nurtan-Gunes, 2018), monitor progress, validate the as-built construction and provide as-built documentation (Han & Golparvar-Fard, 2017).

Images captured on the construction site are a useful way of monitoring construction (Han & Golparvar-Fard, 2017; Koseoglu & Nurtan-Gunes, 2018), with value gained where visual data is organised with BIM. For example, time lapse data can offer images at any specified stage of the construction for comparison against the schedule. However, obstacles and site conditions affect the quality of the imagery and cameras are prone to movements, which require correction. As it stands, the technology available is still unable to correct the impact of inconsistent light (Han & Golparvar-Fard, 2017). More broadly, aligning visual data with BIM can be challenging and further research is required (Han & Golparvar-Fard, 2017).

New collaboration and coordination technologies better connect the construction site and the design office, streamlining DM tasks around coordination and buildability. CDE and BIM-based digital tools allow for a fluid and visual exploration of the design while on the construction site, aiding collaboration and discussion and DM decision making (Koseoglu & Nurtan-Gunes, 2018; see Revizto at Vizerra SA, 2012-2020). Successes in usability could be extended further with Virtual Reality (VR) capabilities (Mehrbod et al., 2019). Digital tools can be used to validate the construction (Koseoglu & Nurtan-Gunes, 2018), but tools are currently limited in their ability to organise visual as-built data (Han & Golparvar-Fard, 2017). Lastly, the tools are limited in their support of DM activities as they focus on the construction phase rather than the design phase. Emmitt describe that the design changes should adhere to process, and require formal documentation (2010), but the tools described in the extended CDE could act to circumvent process and make design changes informal.

Programme and Cost Management (4D/5D BIM)

Construction projects are well known for unpredictability and overrunning schedule, with this worsened with building size and complexity (Gledson & Greenwood, 2017). Research suggests that poor planning can be a greater cause of delays than unforeseeable events and obstacles (Gonzalez et al., 2013 cited in Gledson & Greenwood, 2017).

The 3D BIM geometry can be assigned to scheduling information, allowing construction tasks to be modelled considering space, resources and time; with 4D BIM further offering automation tools to streamline construction processes. Where scheduling is separate to the BIM, it can be difficult to understand construction processes and the schedule accuracy (Sacks et al., 2018).

4D BIM can simulate and visualise construction sequences virtually, facilitating DM processes of communication, collaboration and decision making (Boton, 2018; Elghaish & Abrishami, 2020; Gledson & Greenwood, 2017; Sacks et al., 2018), while also improving project predictability (Boton, 2018). It follows that 4D visualisation facilitates DM buildability assessments for optimisation and efficiency (Boton, 2018). To establish a 'value-stream', the design information is utilised to plan and schedule construction and is interrogated for buildability and efficiency (Sacks et al. 2018).

5D BIM further incorporates cost, allowing both the 3D geometry and the 4D scheduling information to be utilised for costing activities. 5D BIM automates many costing activities for efficiency and improved accuracy (Vigneault et al., 2019). However, the information contained in BIMs is often inadequate in terms of geometric accuracy and completeness. This can mean that the capabilities of 5D BIM are not fully realised (Smith, 2016). 5D quantity take-off is limited in that quantities need to be exported to a spreadsheet. Full estimates are not fully supported by 5D BIM as they require wider considerations about the construction process. As such, cost estimates are not parametrically linked to the BIM and quantities need to be renewed if there are any design changes (Sacks et al., 2018).

In line with lean principles (Emmitt, 2010), high standards of cost management achieved early allow DM-based discussion and review for efficiencies. BIM is central in supporting interim estimates which highlight budget issues and inefficiencies quickly. The earlier the contractor can participate in the 5D cost management, the greater the confidence and accuracy in cost management outputs (Sacks et al., 2018).

An IPD approach implements early collaboration and planning processes for value generation and waste elimination (Elghaish et al., 2020). Elghaish et al. (2020) integrated 4D and 5D BIM into IPD and developed a Genetic Algorithm (GA) to optimise scheduling and costing. The research utilises Navisworks 4D and 5D BIM tools as a single source for all required digital tools, eliminating the process of importing and exporting in and out of different systems. This required the development of a C# plug-in utilising the Autodesk C# API. The proposed new system integrates Activity-Based Costing (ABC) with the use of an activity library. Multi-criteria for GA based schedule optimisation were available for selection.

BIM is an important tool in ensuring the efficiency and accuracy of scheduling (Sacks et al., 2018) and costing activities, with the capacity to link 3D geometry, scheduling and costing information together (Vigneault et al., 2019). Capabilities in 4D BIM allow construction sequences to be modelled, contrasted and visualised for DM collaborative analysis and discussion (Boton, 2018; Gledson & Greenwood, 2017; Sacks et al., 2018). There have been focused research efforts into schedule optimisation based on multi-criteria (Elghaish et al., 2020).

Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR)

Virtual Reality (VR) can extend the visualisation capabilities of BIM and can be used to explore construction or to promote ideas to clients (Emmitt & Ruikar, 2013). Models of n-dimensions can be visualised with VR (Bolton, 2018), Augmented Reality (AR) (Chu et al., 2018) and Mixed Reality (MR) (Alizadehsalehi et al., June 2019; Wang & Kim, 2019).

AR facilitates the visualisation of a virtual model in the real-world (Alizadehsalehi et al., June 2019) improving navigation and interactivity (Fiorentino et al., 2012 cited in Mehrbod et al., 2019) and can be used to visualise construction sequences, providing an immersive experience in the physical world (Alizadehsalehi et al., June 2019; Chu et al., 2018), improving the quality of DM decisions and the DM decision making process (Chu et al., 2018), particularly as it supports design stage review.

Further to supporting design review through enhanced visualisation, Chu et al., describes how VR capacities in interactivity can be applied to improving information flow. The increasing complexity of construction projects leads to inefficiencies due to increasing amounts of data, information and systems to conduct construction DM activities (2018). The accessibility of design information can be a source of inefficiency (Chu et al., 2018; Mehrbod et al., 2019) because it increases the need to find and coordinate disparate and disjointed pieces of design information (Mehrbod et al., 2019).

VR technology can improve interactivity by improving the efficiency of 2D to 3D information transitions. (Broll et al., 2014 cited in Mehrbod et al., 2019). AR has the potential to provide enhanced functionality, including filters, to drill down into design information, improving the accessibility of information and reducing the effort required to complete DM tasks. Research suggests that AR can improve efficiency in information retrieval in terms of time and accuracy and further can reduce cognitive effort and loading on project participants (Chu et al., 2018). MR builds on AR, allowing virtual content to be manipulated as it is viewed (Alizadehsalehi et al., June 2019). For implementation, MR requires technologies such as Microsoft HoloLens (Alizadehsalehi et al., June 2019; Wang & Kim, 2019) and the Unity Games engine, and can add value to projects when integrated with a lean workflow (Alizadehsalehi et al., June 2019).

VR technology could be a key feature improving usability in applications where BIM is not performing as expected, as is often the case in DM collaborative buildability assessments (Chu et al., 2018; Mehrbod et al., 2019). In a collaborative context, interactivity is shared by participants to achieve common DM tasks and goals (Isenberg, 2011 cited in Boton, 2018), supporting DM decision making processes (Berg & Vance, 2017 cited in Boton, 2018). It follows that VR is able to integrate the project team (Issa, 2005 cited in Boton, 2018). Research has suggested the benefits of utilising VR in the construction sector. However, in a 4D context, VR processes are still limited and are not yet achieving outcomes (Boton, 2018).

Point Cloud

Point cloud has been applied to robotics navigation, automation in construction and construction health and safety. In the context of DM, point cloud has strengths in construction progress monitoring and construction quality assessments (CQA) (Wang & Kim, 2019).

The as-built construction is often different to its design information due to design changes over the course of the construction process (Wang & Kim, 2019). The Hackitt Review has recommended that as-built construction is recorded and validated against the original design information for safety reasons (May 2018). Point cloud technology can be used to create as-built BIMs to perform CQAs and validation throughout the construction process (Han & Golparvar-Fard, 2017; Wang & Kim, 2019) and can also be used to monitor the progress of construction (Wang & Kim, 2019). 4D BIM buildability analysis and validation can be incorporated into construction activities by using point cloud for the timely capture and control of productivity lapses (Omar et al., 2018 cited in Boton, 2018), with 4D point clouds captured and validated against 4D as-designed BIMs to support scheduling and design (Lin & Golparvar-Fard, 2016 cited in Han & Golparvar-Fard, 2017).

There are a number of different methods available in point cloud technology. These include:

- **Laser Scanning:** Laser scanning is strong for accuracy (Rebolj et al., 2017) but is costly and time consuming (Pučko et al., 2018; Rebolj et al., 2017).
- **Photogrammetry:** Photogrammetry is not as expensive as laser scanning and has lower but arguably acceptable accuracy and quality, depending on the use (Rebolj et al., 2017).
- **Videogrammetry:** Similar to photogrammetry, videogrammetry is a lower to mid-range solution and produces acceptable results at a lower cost (Rebolj et al., 2017).
- **Range (Depth):** Depth scanning is mid-range in terms of cost, being expensive compared to photogrammetry but cheaper compared to laser scanning. Results are reasonable, with particular strengths on small projects where distances are small (Omar & Nehdi., 2016 cited in Pučko et al., 2018).

There have been various research efforts into the automation of point cloud scan plans (Rebolj et al., 2017). Researchers have developed an algorithm to identify efficient scan plans considering data properties concerning quality (Tang & Alaswad 2012 cited in Rebolj et al., 2017). Other research has looked at achieving efficiency in the amount of data collected taking into account optimum scanning points (Biswas et al., 2015 cited in Rebolj et al., 2017); with further efforts directed into improving the automation of scan planning (Zhang et al., 2016 cited in Rebolj et al., 2017).

The long-term objective is for as-built scanning and validation to be ongoing throughout the construction process, while attaining good point cloud performance in terms of quality properties: level of detail (LOD), local density, local accuracy and level of scatter (LOS) (Rebolj et al., 2017; Wang & Kim, 2019). Rebolj et al. (2017) developed a method for assessing different point cloud scanning technologies, with the intention of using the workers as mobile scan points for instantaneous, ongoing and real-time CQAs.

Real-time construction monitoring is important so that lapses in construction progress can be picked up quickly and errors in the construction can be addressed and resolved in a timely manner (Pučko et al., 2018; Wang & Kim, 2019). Pučko et al. implemented a system which utilised time intervals to scan, with depth scanning, the relevant section of as-built construction at short-range. The resulting partial point cloud could then be registered, with a time, to a 4D BIM for validation (2018). In realising real-time CQA monitoring, research centres on accurate and suitable automated registration and alignment of as-built point clouds (Lei et al., 2019; Pučko et al., 2018).

Point cloud is valuable in construction progress monitoring (Lei et al., 2019; Pučko et al., 2018; Wang & Kim, 2019). Depth imaging can be used on moving entities to provide short-range incomplete as-built point clouds, which when federated to an as-designed BIM, provide the potential for 4D validation of the construction. However, research challenges remain in the registration and alignment of point clouds (Pučko et al., 2018) for greater levels of accuracy and reliability (Lei et al., 2019). Moreover, although as far as possible, construction is planned and the design information is finalised before construction according to lean principles (Emmitt & Ruikar, 2013), continuously monitoring the construction will allow the DM to identify any process, buildability or coordination issues during construction and provide timely rectification (Pučko et al., 2018; Wang & Kim, 2019)

Artificial Intelligence (AI)

AI has the ability to solve complex and uncalculatable problems from existing datasets to provide predictions and insight (Darko et al., 2020). Machine Learning (ML) falls within the AI subject area and includes Neural Networks (NN), support vector machines (SVM), Gaussian Mixture (GM), Reinforcement Learning (RL), Deep Learning (DL) and probability methods such as naive Bayes. Broadly, ML is the capability a computer has to learn from existing information. NNs achieve this capability by drawing on the biological structure of the brain to conduct processes iteratively or to perform classification tasks by looking at previous successes (Darko et al., 2020).

The construction sector produces high volumes of data in the form of BIMs, site records, post-occupancy evaluation (Chen et al., 2016), visual capture (Rahimian et al., 2020) and IoT (Rogage et al., 2019); with the further the potential to apply analytics to communications (Wang, Thangasamy, Hou, Tiong and Zhang, 2020). The data collected over the course of construction projects presents an opportunity to drive efficiencies and productivity (Bilal et al., 2016 cited in Darko et al., 2020).

Darko et al. (2020) used centrality metrics to identify important and influential areas of research interest, with results showing optimisation receiving a lot of research interest, possibly due to the need to automate and streamline complex processes. Genetic Algorithm (GA) is shown to be the go-to method in optimisation tasks and is a key theme in the literature. NN, ML, Fuzzy Sets (FS) and Fuzzy Logic (FL) are also key themes, with research gaps in the use of methods such as adaptive neuro-fuzzy inference system (ANFIS) and differential evolution (DE) among others.

Research efforts around Key Performance Indicator (KPI) assessments are immature and underdeveloped in their application of AI, with research into cost and risk management making little or poor use of BIM, despite the capability of BIM to provide tools in these areas. As such, there are research gaps in utilising AI with BIM for KPI assessments (Darko et al., 2020). For example, 4D as-built validation can be used to monitor progress and infer productivity in construction (Han & Golparvar-Fard, 2017).

Juszczyk provides an example of how BIM data can be used in implementing a NN for data analytics related to cost (2017). However, much research shows a reliance on data extraneous to the BIM(s). Chen et al. (2016) devised a system to include this data as ‘dynamic’ BIM data for better integration of BIM and data technology. The system, referred to as CloudBIM, was available to project participants as a CDE. Within CloudBIM, WebGL was used for visualisation, Hadoop Bigtable was used for Big Data storage and MapReduce was used for data processing. The system parses the 3D BIMs and stores the data in a NoSQL database format; further data from construction projects can be stored alongside in the same database for data processing. Zhou et al. (2020) further retained graph-based data relationships in the storage of BIM Big Data.

AI is often used to process Visual Big Data for use in supporting construction tasks (Darko et al., 2020; Han & Golparvar-Fard, 2017). Analytics can be used to automate the alignment of visual data to the BIM (Han & Golparvar-Fard, 2017), perform object recognition (Darko et al., 2020; Han & Golparvar-Fard, 2017; Wang & Kim, 2019) and object classification. CNNs are a form of deep NN often applied to achieve these functionalities in visual data analytics, while also being well known in areas such as Natural Language Processing (NLP). Popular applications for CNNs in DM include construction site safety and structural damage, such as identifying concrete cracks. CNNs are able to process imagery by breaking the pixels down into arrays based on colour, and are able to perform processes in parallel for the identification of arrangements and objects (Darko et al., 2020).

AI and ML are disruptive technologies with strategic management and process design required for implementation and maximum benefit (Darko et al., 2020). Increasing complexity, leading to high volumes of data, presents an opportunity to utilise computing for learning (Bilal et al., 2016 cited in Darko et al., 2020). However, data extraneous to the BIM might be required, and systems have been developed in the literature for the combined storage and processing of BIM and wider data (Chen et al., 2016; see also Zhou et al., 2020). A wide range of methods are available within the AI subject area which are applicable to DM and construction sector problems, with the potential to provide efficiencies. Optimisation has been a key research interest, while research is required in integrating BIM with AI-based KPI assessments. The use of CNNs to organise and understand visual information has also been a key research area, with applications including safety management and the detection of structural defects (Darko et al., 2020).

Blockchain

Blockchain technology is developing as part of the digital transformation of the construction sector, with changes to processes required for its application and implementation (Li et al., 2019; Mathews et al., 2017; Nawari and Ravindran, 2019). As such, Blockchain is a disruptive technology (Li et al., 2019; Mathews et al., 2017; Nawari and Ravindran, 2019; Turk & Kinc, 2017), able to achieve efficiencies and increased productivity, with use cases in collaborative DM, IoT for CQAs, post-evaluation, smart contracts (Li et al., 2019; Nawari and Ravindran, 2019) and smart cities (Li et al., 2019).

Blockchain, also referred to as Distributed Ledger Technology (DLT), is a peer-to-peer network, offering a decentralised approach to the storing and updating of information (Kinnaird et al., 2017; Li et al., 2019; Nawari and Ravindran, 2019). Storing information in a single space, such as a cloud service, can be subject to security and information management concerns (Kinnaird et al., 2017; Nawari and Ravindran, 2019). As soon as participants upload information to a central server, they lose control over that information, whereas a distributed network ensures that contributed information stays on the systems of those who made the contribution (Petri et al., 2017).

The implementation of blockchain in collaborative working practices looks to have the potential to resolve the shortfallings of CDEs by enhancing security and embedding legal rights (Kinnaird et al., 2017; Li et al., 2019), improving DM methods of collaboration and trust (Li et al., 2019; Mathews et al., 2017; Nawari and Ravindran, 2019). In a change to process, blockchain holds the potential to remove lines of management and leadership, as participants can upload their contributions directly. This enhances trust further, making participation more equal and direct (Li et al., 2019; Matthews et al., 2017). In the case of new recommendations set-out by the Hackitt Review (May 2018), blockchain can be applied to the archiving of a ‘thread’ of information (Li et al., 2019).

Furthermore, blockchain makes it possible to embed contracts in code for the automatic payments of services. Smart contracts functionality can be further embedded into project bank accounts (PBAs) and cryptocurrency functionality, with specific currencies such as EtchCoin (Li et al., 2019) and AECoin (Nawari and Ravindran, 2019) created for the construction sector (Li et al., 2019; Nawari and Ravindran, 2019). The automation of payments could be transformational for the construction sector (Kinnaird et al., 2017; Li et al., 2019), as the government is taking action to improve identified problems with late payments to ensure stability in the supply chain (HM Government, March 2016). Nawari and Ravindran (2019) use a Hyperledger Fabric for greater flexibility with smart contracts functionality to describe and implement a model checking and model validation BIM process. Moreover, Wang, Wang, Hu, Gong, Ren, and Xiao (2020) suggest a smart contract process for the management of precast concrete construction, organising site deliveries and monitoring any conflict or problems.

A distributed peer-to-peer network utilises participants’ hardware as servers to hold an authoritative copy of BIMs federated to a single model, which is updated when required. Servers can be different cloud providers and the integration of different cloud services can achieved with existing applications/providers such as CometCloud, which is open-source, or IBM Cast Iron Cloud Integration (Petri et al., 2017). A peer-to-peer network can be implemented without necessarily implementing blockchain. Petri et al. (2017) looked at collaborative data sharing by federating distributed cloud datasources in their ‘clouds for coordination’ (C4C) framework, supporting 2 APIs and a Revit BIM plug-in. Interactions facilitated by an API allow participants to communicate as ‘publishers’ or ‘subscribers’ and identifies participant roles and responsibilities. Another API for rendering the BIM model uses this information, alongside an issue status, to inform access and authorisation to different parts of the federated BIM.

Barriers to the implementation of blockchain include skill shortages and cost. Implementing blockchain for information management and information sharing from one datasource, in place of or enhancing a CDE, requires more fundamental changes to BIM processes and workflows (Li et al., 2019). Factors for deciding on a Blockchain implementation include whether the blockchain needs to be permissioned or not, how scalable the blockchain needs to be, security and privacy requirements, data requirements, and hardware and software requirements for data collection and functionality (Li et al., 2019; Nawari and Ravindran, 2019). Digital tools relying on blockchain might look to utilise open-source or commercial blockchain implementations, rather than provide an embedded implementation (Turk & Kinc, 2017). Li et al. (2019) have proposed a decision tree to help system architects make decisions over the suitability of blockchain for the purposes of an application. This suggests that blockchain is suitable where BIMs are complex, where there is data collection from site, where a digital record of design decisions and changes is required, where automation is required, and where the speed of the network is not important.

Blockchain is a disruptive technology with the capacity to enhance DM methods of trust and collaboration in the construction sector (Li et al., 2019; Matthews et al., 2017; Nawari and Ravindran, 2019). The existing CDEs require participants to upload information to a single shared online space, potentially accessible to everyone on the project team; this is unacceptable from a security perspective (Kinnaird et al., 2017; Nawari and Ravindran, 2019). Blockchain is a distributed, decentralised peer-to-peer system, whereby a consistent copy of the centralised information is kept by each node. This centralised information, or the blockchain, cannot be changed or altered without passing stringent validation and authorisation requirements (Kinnaird et al., 2017; Li et al., 2019; Nawari and Ravindran, 2019). As the blockchain is responsible for validating each transaction/exchange, the automation of payments with smart contracts is a big opportunity to reform the sector’s endemic trust issues (Li et al., 2019; Nawari and Ravindran, 2019).

SOLUTIONS AND RECOMMENDATIONS

As BIM is a process (Azhar et al., 2012), BIM should be implemented with IPD and alongside DM methods of communication, collaboration and trust as one and the same (Fig 2). The DM should use early engagement to develop collaborative and trusting relationships among participants in the project team (Piroozfar et al., 2019). BIM can be used as a communication tool (Ajayi et al., 2019) to integrate information and manage information flow (Tvedt et al., 2019) according to the ISO 19650 standard.

Conflict surrounding users’ digital literacy and the standard of BIM tools (Gledson, 2016) can be understood in light of the 4th industrial revolution (Alaloul et al., 2020) and the status of BIM as incomplete and a developing innovation (Alaloul et al., 2020; Sacks et al., 2018). This should not deter construction companies from exploiting BIM and digitalisation, and the construction sector needs to do so to bring its performance in line with other sectors (Alaloul et al., 2020).

Alongside BIM implementation (Piroozfar et al., 2019), DMs should use strong social skills, pay attention to sources of conflict (Tvedt et al., 2019) and use good prevention and intervention measures according to Malik & Lenka (2019) to ensure that stress does not become embedded in the project team (see Ajayi et al., 2019 and Samnani & Singh, 2016). Successful collaborative working will establish a good learning, decision and design process (Tvedt et al., 2019) to ensure information flow (Uusitalo et al., 2019) and the 'pull' of value. Further technologies can be integrated with BIM including communication and collaboration tools, programme and cost management tools, VR, point cloud, AI and blockchain. These enhancements can be applied to support digitally-enabled DM tasks and methods.

The following table provides details on DM relevant digital tools available commercially or on an open-source basis. It is further possible to implement bespoke solutions or carry out research and development where commercial and open-source solutions fall short.

CONCLUSION

The construction sector's digital transformation includes BIM integrated digital advances in collaboration and communication, programme and cost management, VR, AI and blockchain. These technologies can be applied to DM activities and methods: collaboration and coordination, optimisation, as-designed and as-built validation, and security and trust (Table 1).

Summary

BIM is a process for the integration of the project team (Azhar et al., 2012; Piroozfar et al., 2019) and is central to a collaborative way of working (Antwi-Afari et al., 2018). BIM adoption and implementation is managed at project outset as part of IPD (Piroozfar et al., 2019). As such, there are dual relationships between DM, IPD and BIM based around communication and collaboration (Fig 2). It follows that the DM design process is a learning and decision making process digitalised or partially digitalised by BIM (Tvedt et al., 2019). Other advanced disruptive technologies can be integrated with BIM to enhance BIM and provide further support to DM methods, activities and processes.

The extended CDE, as described by Koseoglu and Nurtan-Gunes, provides collaboration and coordination tools supporting DM coordination, buildability and design review activities, by creating a more fluid communication channel between the construction site and the design office, also providing validation functionality (2018). Tools which support communication will also foster trust within design team relationships (Uusitalo et al., 2019). However, extended CDE tools focus is on the construction phase. Therefore, extended CDE tools may provide limited support for lean, and may circumvent and make informal some DM processes.

Vigneault et al. describe how 4D and 5D BIM link programming and costing information to the 3D geometry (2019) achieving efficiency and accuracy (Sacks et al., 2018) in DM activities of programme and cost management. According to Boton, 4D BIM enables enhanced visualisation of the construction by including the time dimension in the DM design review activity. VR can be used to enhance and extend visualisation further (2018) and can also be used to improve the usability of BIM in DM collaborative buildability assessments (Mehrbod et al., 2019).

Table 2. This table presents a list of the DM relevant technology products which are available commercially or which are available on an open-source basis.

		Technology Products
BIM Modelling (see Abanda et al., 2015)	Architecture	• Autodesk Revit Architecture: https://www.autodesk.co.uk/products/revit/architecture • ArchiCAD: https://www.graphisoft.com/archicad/ • Bentley MicroStation: https://www.bentley.com/en/products/brands/microstation
	Rendering	• 3ds Max: https://www.autodesk.co.uk/products/3ds-max/overview • Vectorworks: https://www.vectorworks.net/uk/make-the-move • Maya: https://www.autodesk.co.uk/products/maya/ • Autodesk Revit: https://www.autodesk.co.uk/products/revit/overview
	Structures	• Autodesk Revit Structures: https://www.autodesk.co.uk/products/revit/structure • Tekla Structural Designer: https://www.tekla.com/uk/products/tekla-structural-designer • Tekla Structures: https://www.tekla.com/uk/products/tekla-structures
	Civil Engineering	• AutoCAD Civil 3D: https://www.autodesk.co.uk/products/civil-3d/overview • Tekla Civil: https://www.tekla.com/products/tekla-civil • Autodesk Infrastructure Design Suite: https://www.autodesk.co.uk/suites/infrastructure-design-suite/overview • Bentley OpenRoads: https://www.bentley.com/en/products/brands/openroads
	Mechanical & Electrical	• Autodesk Revit MEP: https://www.autodesk.co.uk/products/revit/mep • Bentley OpenBuildings: https://www.bentley.com/en/products/brands/openbuildings • MagiCAD [Autodesk plug-in]: https://www.magicad.com/uk/what-is-magicad-for-mep/ • DDS CAD: https://www.dds-cad.net/
Collaboration & Coordination	Clash Detection	• Navisworks: https://www.autodesk.co.uk/products/navisworks/overview • Solibri: https://www.solibri.com/
	Collaboration & Coordination	• BIM 360: https://www.autodesk.com/bim-360/ • Viewpoint: https://vfpdocs.viewpoint.com/ • Asite: https://www.asite.com/ • GroupBC: https://www.groupbc.com/our-products • Revizto: https://revizto.com/en/ • BIMtrack: https://bimtrack.co/ • BIM Anywhere: https://bimanywhere.com/ • Bluebeam Revu: https://www.bluebeam.com/uk/ • Tekla BIMsight: https://www.tekla.com/tekla-bimsight/ • Dalux: https://www.dalux.com/gb/ • Assemble: https://assemblesystems.com/ • Synchro Field: https://www.bentley.com/en/products/product-line/construction-software/synchro-field
	Facilities Management	• GliderBIM: https://gliderbim.com/ • Twinview: https://www.twinview.com/
Programme & Cost Management	Project Management	• Microsoft Project: https://products.office.com/en-gb/project/project-management-software • Primavera P6: https://www.oracle.com/applications/primavera/products/project-portfolio-management/
	4D BIM (Programme Management)	• Navisworks Manage: https://www.autodesk.co.uk/products/navisworks/overview • Visual 4D Simulation (Innovaya): http://www.innovaya.com/prod_vs.htm • Synchro Pro: https://www.bentley.com/en/Products/Product-Line/Construction-Software/SYNCHRO-PRO • Bentley ProjectWise Manager & ConstructSim Pro: https://www.bentley.com/en/products/product-line/construction-software/synchro-awp • Tekla Structures: https://www.tekla.com/uk • Vico Office Schedule Planner: https://gc.trimble.com/product/schedule-planner
	5D BIM (Cost Management)	• CostX: https://www.exactal.com/en/ • Nomitech: https://www.nomitech.com/ • Innovaya: http://www.innovaya.com/prod_ve.htm • Assemble: https://assemblesystems.com/assemble-sage-integration-request-more-info/ • RIBiTwo: https://www.rib-software.com/en/home • Vico Office: https://gc.trimble.com/product-categories/vico-office-time
Virtual Reality (VR), Augmented Reality (AR) & Mixed Reality (MR)	-	• Navisworks Manage: https://www.autodesk.co.uk/products/navisworks/overview • 3ds Max: https://www.autodesk.co.uk/products/3ds-max/overview • Unity: https://unity.com/ • Wikitude: https://www.wikitude.com/ • Bentley Synchro [Autodesk Revit Plug-In] https://www.bentley.com/en/products/brands/synchro

continued on following page

Table 2. Continued

		Technology Products
Point Cloud	-	• Matterport Cloud: https://go.matterport.com/ • HoloBuilder: https://www.holobuilder.com/ • Trimble Realworks: https://geospatial.trimble.com/products-and-solutions/trimble-realworks • Edgewise 3D: https://www.clearedge3d.com/products/edgewise/ • MeshLab: https://www.meshlab.net/ • LiDAR 360: https://greenvalleyintl.com/software/lidar360/ • MeshLab: https://www.meshlab.net/ • FAROscene: https://www.faro.com/en-gb/products/construction-bim-cim/faro-scene/ • FAROscene Web Share: https://websharecloud.com/ • Leica Cyclone: https://leica-geosystems.com/en-gb/products/laser-scanners/software/leica-cyclone • Leica Pagasus: https://leica-geosystems.com/en-gb/products/mobile-sensor-platforms/capture-platforms/leica-pegasus_two • Flyvast: https://flyvast.com/ • Voxxlr: https://www.voxxlr.com/ • Xtion Pro: https://www.asus.com/3D-Sensor/Xtion_PRO/ • Structure Sensor: https://structure.io/structure-sensor/mark-ii? • CloudCompare: https://www.danielgm.net/cc/ • Bentley Context Capture: https://www.bentley.com/en/products/brands/contextcapture
Artificial Intelligence (AI) & Machine Learning (ML)	Data Analytics Graphics	• PowerBI: https://powerbi.microsoft.com/en-us/
	Data Processing	• Hadoop: https://hadoop.apache.org/ • MapReduce: https://hadoop.apache.org/docs/r1.2.1/mapred_tutorial.html • Apache Spark: https://spark.apache.org/ • Google Cloud: https://cloud.google.com/products/ai • Tensorflow: https://cloud.google.com/tensorflow-enterprise
Blockchain	Distributed Computing	• ProjectWise: https://www.bentley.com/en/products/product-line/project-delivery-software/projectwise-connection-services • Revit Server: https://knowledge.autodesk.com/support/revit-products/downloads/caas/downloads/content/autodesk-revit-server-2020.html • CometCloud: https://cometcloud.rdi2.rutgers.edu/ • IBM Cast Iron Cloud Integration (part of WebSphere): https://www.ibm.com/uk-en/cloud/integration • BIM Server: https://bimserver.center/en
	Existing Blockchain Implementations	• Ethereum: https://ethereum.org/java/#intermediate-articles • NEO: https://neo.org/ • Hyperledger: https://www.hyperledger.org/ • Storj: https://storj.io/

Real-time CQAs and progress monitoring with point cloud allows the DM to identify process, buildability or coordination issues during construction and provide timely rectification (Lei et al., 2019; Pučko et al., 2018; Wang & Kim, 2019), with real-time depth scanning on moving entities an objective and a solution (Pučko et al., 2018). However, in terms lean principles, CQAs and progress monitoring is reactive and construction phase based. Moreover, as-built point clouds have the potential to provide a 'thread' of as-built information as required by the Hackitt Review (May 2018).

It follows that construction produces high volumes of data (Chen et al., 2016), presenting an opportunity to use data to drive efficiencies and productivity (Bilal et al., 2016 cited in Darko et al., 2020). For AI implementation, there reliance on data extraneous to BIMs, with systems developed to deal with this (Chen et al., 2016). AI also has the capacity to support the processing of visual Big Data (Darko et al., 2020; Han & Golparvar-Fard, 2017) for monitoring and validation purposes (Han & Golparvar-Fard, 2017).

Blockchain can be implemented to resolve CDE security concerns (Kinnaird et al., 2017; Li et al., 2019) with the capacity to enhance DM methods of trust and collaboration (Li et al., 2019; Matthews et al., 2017; Nawari and Ravindran, 2019). Research by Petri et al. (2017) on collaborative data sharing shows how a peer-to-peer network can be used to control BIM visibility and contributions.

Limitations & Future Research

BIM is a disruptive innovation (Antwi-Afari et al., 2018) requiring process for implementation (Azhar et al., 2012) with many companies struggling to implement a full transformation (Gledson, 2016). BIM is still developing, with future research efforts directed toward developing BIM tools which support greater levels of detail and which eliminate the need for drawings (Sacks et al., 2018). BIM is a collaborative process, but the ability BIM has to support communication is limited because BIM and other digital communication tools do not yet reflect the varied, subjective and iterative nature of real world communication. Further research is required to understand group working practices in order to improve communication and collaboration, and reduce conflict (Tvedt et al., 2019). Further research is also required around the coordination and DM problem solving process, as BIM still has limitations in terms of interactivity (Mehrbod et al., 2019). Chu et al. researched AR as a possible solution to data extraction inefficiencies, but further research is required to establish the option as worth the implementation cost (2018). Research further suggests VR processes are problematic in the context of 4D BIM (Woksepp & Olofsson cited in Boton, 2018). Moreover, real-time progress monitoring and CQAs utilising point cloud rely on the accurate registration of as-built point clouds to as-designed BIMs (Lei et al., 2019; Pučko et al., 2018).

AI is a disruptive innovation, requiring management and process for implementation (Darko et al., 2020). The same is true of blockchain where implementation requires new workflows, and where further barriers to implementation exist including cost and skill (Li et al., 2019). Future research in AI is required to better integrate BIM when using AI for KPI assessments (Darko et al., 2020), as data for AI applications often require data extraneous to BIMs (Chen et al., 2016). Future research is also required in optimisation to look at a wider range of AI methods to GA, such as ANFIS, DE (Darko et al., 2020). Furthermore, Han and Golparvar-Fard identify limitations in the ability of BIM tools to organise visual data (2017) with the registration and alignment of as-built point clouds to as-designed BIMs also attracting research interest (Lei et al., 2019; Pučko et al., 2018).

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KEY TERMS AND DEFINITIONS

Building Information Model (BIM): A computerised entity which structures and holds information as a representation of a designed or physical asset (ISO 19650-1:2018).

Building Information Modelling (BIM): The collaborative process (Azhar, et al., 2012).

Collaboration: Participants from independent organisations coming together to make equal contributions to project activities and deliver outcomes under the management established for a temporary [construction] project (Emmitt & Ruikar, 2013).

Common Data Environment (CDE): A single shared space where project participants can share and access information according to a process (ISO 19650-1:2018). A CDE is usually web or cloud based.

Coordination: The alignment and integration of design information from different project participants.

Data: Structured figures, symbols or numbers stored on a computer (Bennett et al., 2010).

Design Management (DM): The management of people, processes, and resources on a construction project to deliver value in terms of cost, time, and quality (Eynon, 2013).

Industry Foundation Classes (IFC): IFC was developed by buildingSMART (Sacks et al., 2018) to resolve interoperability problems between different BIM providers (Azhar et al., 2012; see Sacks et al., 2018).

Information: Data presented with meaning to aid decision making (Bennett et al., 2010).

Interoperability: Automated data exchange and transfer capability without the need for the manual processing of that data (Azhar et al., 2012).

Key Performance Indicator (KPI): A variable against which to measure a project's performance.

Parametric: Refers to a BIM whose components/entities are enriched with intelligent properties (Azhar et al., 2012).

Process: A structured step-by-step sequence of actions/tasks starting with inputs to achieve given outputs under different defined circumstances (ISO/IEC 19510, 2013).

Trust: The acceptance of vulnerability based on a belief that the other concerning actor will uphold expected standards of conduct or uphold an agreed contract.

Virtual Reality: VR is best defined as "experience of presence in an environment by means of a communications medium" (Steuer, 1995 cited in Boton, 2018, p. 2). VR is further understood in terms of usability and presence-based variables immersion and interactivity (Boton, 2018).