The role of integrated digital technologies in major design and construction projects: A systematic literature review of the evidence

Dr. Nurain Hassan Ibrahim

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Comments and feedback are welcome. Kindly contact the author at u.d.hassanibrahim@reading.ac.uk

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The role of integrated digital technologies in major design and construction projects: A systematic literature review of the evidence

Abstract

In today’s digital economy, integrated digital technologies such as BIM, play a crucial role in the delivery of major construction and infrastructure projects. The construction industry has been adjudged to be at the verge of a technological revolution, with myriad technologies promising innovative solutions to the industry’s age-old problems of coordination and delivering projects on-time, on-budget and to clients’ specifications, through what has come to be known as integrated project delivery. The step-change in construction practice envisaged has, however, largely remained limited in scope, with variations from one project or firm to another. The systematic review of the evidence in this paper shows how digital collaboration technologies are being used in the delivery of building and infrastructure projects at various stages in the project life cycle and into the life of the assets. This paper reviews the research literature that studies how digital practices emerge in internationally leading projects that are using or developing digital collaborative tools in design collaboration across disciplines. The focus is on the practices, methods and processes that often develop as a result of, or less often, lead to, these technologies. The review was also interested in understanding how the use of digital technologies leads to significant changes (if any) in project delivery, mainly in relation to interoperability with other technologies, work practices of co-located and virtual teams and networks, contractual practices, delivering value to clients and the green design practices that are currently the focus of attention of industry and policy makers. The review then focused on the problems, challenges and potentials of digital collaboration technologies, especially 3D visualisation tools and Building Information Modelling (BIM) solutions. Lastly, the ways in which the literature theorised various phenomena in the field were analysed and the implications for construction practice were expounded.

Keywords: 3D, 4D, BIM, collaboration, coordination, digital technologies, green practices, integration, interoperability, major projects, standardisation, problems and challenges project practices, teams and networks
1 Introduction

1.1 Overview

Collaboration in the Architecture Engineering and Construction (AEC) domain has been a challenge for a long time. Current policy debates indicate that the UK government is interested in working with industry to address this and other challenges confronting the construction industry, to derive full value from, and exploit the growth potential in the "public procurement of construction and infrastructure projects" (Government Construction Strategy, 2011, p. 3). Similar debates are happening internationally, as indicated by the evolving policy agenda in the USA and Denmark, and developments in Australia and Canada among others (Whyte, Lindkvist, & Hassan Ibrahim, 2011). In the UK, government is concerned that the construction industry has not fully taken advantage of the "full potential offered by digital technology" (Government Construction Strategy, 2011, p. 13). As a contribution to this discourse, therefore, this review is quite timely.

In the past few decades, project managers, engineers, architects, and researchers have been exploring and developing different digital technologies and processes aimed at addressing issues surrounding coordination and collaboration in the design and delivery of major building and infrastructure projects. Henderson (1991) captured the importance of 2D CAD modelling technologies in constituting "the basic component of communication" and shaping "the structure of the work, who may participate in the work, and the final products of design engineering" (p. 449). Similarly, Ahmad, Russell, & Abou-Zeid (1995) discussed how IT can help design and construction organisations integrate the myriad construction activities by assisting them in redesigning their functions and processes.

The role of technologies in the construction industry has been discussed from various perspectives, from their impact on the structure of construction (Bröchner, 1990), in diffusion of innovation (Peansupap & Walker, 2006; Fox & Hietanen, 2007; Harty, 2010) and their use by small and medium-sized construction firms (Acar et al., 2005). Furthermore, while there is great policy and practice interest in increasing the use of new technologies, the research evidence base that can inform this is not as robust. For instance, there has been concern over the lack of clarity about the actual ways in which BIM is used in projects or what is myth and what is reality (Eastman et al., 2008; Dossick & Neff, 2010b). The research landscape, therefore, is quite in need of a systematic review of the literature, to unearth the evidence on how digital collaboration technologies are actually used and to what effect. This is what this paper reports on. It presents a systematic review of the evidence on the most recent research on digital collaborative technologies and practices in internationally-leading building and infrastructure projects.
1.2 Aims and objectives

The aim of this study is to unearth, through a rigorous process, the research evidence about how digital technologies are changing organisational practices in major projects. This also involves looking at the methods and processes that develop as a result of, or lead to, the use of these tools and the impact on project delivery, especially in relation to other technologies, project management and the green design practices that are currently the focus of public policy. Finally, it is aimed at a better understanding of how design innovation may be sustained into the future and the next generation of tools and processes that need to be (or are being) developed to achieve that. The objectives are:

1. To conduct a systematic review of the research literature using the methodology detailed below.
2. To identify, synthesize and translate the evidence on the use of digital tools in actual construction projects.

1.3 Methodology

The methodology adopted for the review is based on the systematic review methodology originally developed in evidence-based medicine (Mulrow, 1994; Mulrow, Cook, & Davidoff, 1997). This was adapted for the management field (Tranfield, Denyer, & Smart, 2003; Pittaway et al., 2004; Rousseau, Manning, & Denyer, 2008; Denyer & Tranfield, 2009) and was in turn adapted for the purpose of this review. This was done through a series of meetings and refinements by the review team and one consultation meeting with two industry experts. The result was a document describing the methodology in detail, the key elements of which are briefly highlighted below.

A kick-off meeting was held by the author and three other colleagues to agree on the methodology, an adaptation of Pittaway et al., (2004) Tranfield et al., (2003). This included agreeing on the aims, objectives, and questions of the review, identifying initial keywords, key journals and databases, and agreeing on the inclusion and exclusion criteria for the literature (see Appendix A). Other online resources for accessing industry literature were discussed. Factiva was mentioned as a useful resource which later turned out not to be the case. A document outlining the different aspects and stages of the review was circulated for comments. This was further discussed and refined in a series of meetings as the review progressed. A meeting involving two industry experts from the ICE Information Systems (IS) panel was also held and their input sought, which helped in shaping the methodology. The methodology was in three main parts; a literature search, relevance rankings and the review proper. The former two are briefly discussed below, while the latter is discussed in the next section.

Extensive literature searches were carried out over several weeks in August, September, and October 2010, covering the major academic databases including ISI Web of Knowledge, ScienceDirect, EBSCO, and ICONDA. Construction databases searched include ARCOM, Intute, BUBL, PLANEX, Urbadoc and ICE Virtual Library. OneSource – Global Business Browser, thought to be an alternative/complement to Factiva for grey/trade literature turned up mostly country and industry reports, an analysis of which indicated that they did not discuss issues relevant the review. An
EndNote library of academic and industry literature, suggested by members of the ICE-IS panel for a previous project, was also consulted and some relevant articles were selected. Notes and observations on the searches and the challenges faced were recorded carefully. The following search terms earlier identified at the methodology meetings were used to construct search strings in various combinations, using delimiters such as publication date and type.

Design (w) innovat*(w) digital; 3D CAD; Integrated (w) software (w) solution*; Integrated (w) software; BIM; Building (w) information (w) model*; Practice* (w) digital; Organisation* OR organising (w) practice* OR process*; Management (w) project OR practice*; Digital prototype*; E-infrastructure; Construction (w) infrastructure*; Building design; Architectur*; AEC; Collaboration; major OR international (w) project

This was done iteratively, with additional keywords incorporated based on the results of previous searches. Next, the abstracts of the selected literature were re-read and ranked according to the author’s perception of relevance and based on the inclusion/exclusion criteria adopted. Two academic experts also recommended some relevant literature. A total of 175 articles/book sections were selected at this stage and exported to an Excel spreadsheet along with their abstracts. These were then re-read more carefully and a preliminary relevance ranking given as follows: v (very relevant); v to m (very to moderately relevant); m to l (of moderate to low relevance); and l (of low relevance). The articles were subsequently ranked A, B, C and D by the author and re-ranked separately by a colleague, with only a few divergences. Finally, the first and second rankers sat down with a third colleague and reviewed the two rankings to come up with a final ranking. At this stage, it was also decided that only those ranked A, B, and C may be included in the review.

1.4 General description of the evidence

The general description of the evidence in this section covers literature found using a search statement that encompasses the overall aim of the review and then selected based on the relevance rankings earlier mentioned. The review also mainly covers literature ranked ‘A’ (42 of the 175), in line with Tranfield et al.’s (2004) precedent, based on the relevance criteria earlier described. The abstracts of the A-ranked literature were then imported into the qualitative analysis software NVivo and coded to identify themes that would focus and frame the review. Subsequently, elements of the B- and C-ranked literature and back searches from articles suggested by the discipline experts were included in the discussion where appropriate.

Slightly more than half of the A-ranked literatures reviewed for this paper are qualitative case studies of (mostly) large-scale construction projects. These investigated project practices, especially in relation to the use of digital technologies, and often involved mixed-methods; interviews, ethnographic observations, surveys of design professionals and other experts involved in project activities. One of these studies (Taylor & Bernstein, 2009) combined qualitative and quantitative approaches to analyse BIM use in multiple projects across several firms. In at least three studies (Hartmann & Fischer, 2007; Staub-French & Fischer, 2007; Staub-French & Khanzode, 2007), the researcher(s) participated actively in the project teams, for up to a year in one instance (Hartmann &
Fischer, 2007). Although the studies’ authors’ reflections on the potential for researcher bias were not evident, the role played by the researchers was transparently reported.

Due to the paucity of the research evidence, some of the inclusion and exclusion criteria earlier mentioned were relaxed in the review process. For instance, although the criteria excluded experimental or developmental studies, five of the studies (Bellamy et al., 2005; Bibby, Austin, & Bouchlaghem, 2006; El-Tayeh & Gil, 2007; Babic, Podbreznik, & Rebolj, 2010; Doloi, 2010) demonstrated their applicability in a real project environment and were, therefore, included in the review. Similarly, three other theoretical studies deemed to be relevant by the author or one of the two academic experts consulted, were included. These were based on rigorous analyses of trends and contextual issues in the construction industry that are of relevance to the review and backed by previous research (Froese, 2010; Grilo & Jardim-Goncalves, 2010; Isikdag & Underwood, 2010). Finally, the studies also include two reviews, one of the literature on systems integration and collaboration in the construction industry (Shen et al., 2010) and the other (Cerovsek, 2010), of important BIM issues being grappled with in major projects, such as interoperability, integration, model-based communication, and collaboration. Two industry-based surveys (Young Jr., Jones, & Bernstein, 2008; Young Jr. et al., 2009) of BIM adoption and implementation are also included. Appendix B lists the authors, study types (e.g., case study, survey, etc.), main or relevant findings and comments on this author’s judgment of the strength of the evidence of the reviewed literature.

2 Review (thematic analysis)

This thematic analysis is based on the major themes that emerged from the coding of abstracts in NVivo and the subsequent review of the articles. The aim of the NVivo coding, as earlier noted, was to aid the identification of the most important issues covered by the literature and, in line with the methodology adopted by Pittaway et al. (2004, p. 141), reduce the need to review every “article in its entirety”. This also had the advantage of enabling the reviewer to begin to appreciate the emerging themes, group the articles according to these themes and make a preliminary judgment about the quality of the evidence (Tranfield et al., 2003; Pittaway et al., 2004). The major themes thus identified are a) integration, b) interoperability (technical and non-technical, including standards), and c) examples of actual practices (implementations, benefits, problems, and resolutions). These are further discussed in the next section.

2.1 Integration:

Integration is an underlying, though not always clearly evident theme in the reviewed articles and this can be broadly divided into two; the integration of people and processes, and the integration of systems (i.e., interoperability issues) that is necessary to achieve the former. The former is usually treated in one of 2 ways, viz: 1a) integration of some stages and disciplines of the project life cycle, b) across the entire project life cycle and/or through asset life; or 2) with a focus on building teams and networks. These are discussed below, while interoperability is discussed in a separate section.
2.1.1 Stages/disciplines

The early stage of the project continues to receive significant attention in the literature (see Bellamy et al., 2005; Khanzode, Fischer, & Reed, 2005; Yoo, Boland Jr, & Lyytinen, 2006; El-Tayeh & Gil, 2007; Ewenstein & Whyte, 2007; Hartmann & Fischer, 2007; Hartmann, Gao, & Fischer, 2008). Young et al. argue that BIM as a design tool was originally aimed primarily at architects (Young Jr. et al., 2009, p. 46). In another survey, it was found that “architects are the heaviest users of BIM with 43% using it on more than 60% of their projects” (Young Jr. et al., 2008, p. 2), while Samuelson (2008) reported a reduction in the use of hand drawings among architects and technical consultants.

However, the aggregated results of 26 case studies of areas of application of 3D/4D models in major construction projects found that “most of the projects have applied 3D/4D models for only one application area in one project phase” (Hartmann et al., 2008, p. 782). Indeed, a breakdown of the applications in the design and construction phases indicates that the majority are in the former phase (Hartmann et al., 2008, p. 779). Similarly, the findings of a survey conducted by Howard & Björk (2008) indicated that BIM solutions appear too complex for many and as such, may need to be applied in limited areas initially. The use of digital tools from an organisational, rather than a purely technological perspective, has been discussed by Yoo et al. (2006) and Ewenstein & Whyte (2007), although the latter described mostly paper-based tools.

Yoo et al. (2006), however, focused on the use of mainly digital representation tools, how early in the project they are deployed, for what purposes, how tightly-coupled, and how extensive. For instance, in one of the projects they studied, only digital representation tools were used in the entire design process. In the other three cases, however, both digital and paper representation tools were used in a tightly-coupled manner. Effective collaboration in one of the cases was achieved through a “dialogue among the actors engaged in doing the work as equals, enabled by a centralised 3D database” (Yoo et al., 2006, p. 222). Khanzode et al. (2005) discuss how 3D/4D CAD and Lean production methods are combined and how the project team organised itself in such a way as to take advantage of this combination and create maximum value and continuous flow of information during the early design phase of a major healthcare project.

Hartmann & Fischer (2007) discussed the use of 3D/4D models to support the constructability review process by supporting the communication and generation of knowledge. Similarly, Doloi (2010) put forward a research-based argument on the benefits of a simulation approach in managing design at an early stage of a project. These include the ability to quantify the impact of changes and the functionality to make those changes, thereby allowing design professionals to analyse what-if scenarios and fine tune the design over the project lifecycle.

Other stages and disciplines covered in the literature include mechanical plumbing and electrical (MEP) (Dosick & Neff, 2010b), prefabrication (Babic et al., 2010), structural (Robinson, 2007), and the construction phase (Goedert & Meadati, 2008). Robinson (2007) argued that a plethora of software solutions (including BIM) have enabled a remarkable shift in structural steelwork detailing from 2D drawings to 3D product modelling. Babic et al. (2010) looked at how mass production prefabrication processes are integrated with construction site activities. This was achieved by using BIM as a link between an enterprise resource planning (ERP) information system and CAD tools, with reported benefits to project progress monitoring and material flow management. Dosick & Neff
(2010b) examined the use of BIM technologies for MEP and fire life safety systems coordination and how the introduction of BIM influences collaboration and communication.

2.1.2 Project/asset lifecycle

Yet other studies investigate the use of digital collaboration technologies in several stages of the project life cycle. However, they often stop short of examining use throughout the entire project life cycle or beyond that into operations, the latter usually discussed only in terms of the potential. For instance, through several short case studies, Fischer (2003) illustrated “how virtual building tools enable designers, builders, and owners to test any aspect of a project’s design, organization, and schedule before committing significant resources to the project”, while Hartmann & Fischer (2007) showed how 3D/4D models support the communication and generation of design, construction sequencing, and scheduling knowledge. Similarly, Nakamura et al. (2006) investigated how 3D CAD information was used as a collaborative tool for the planning and coordination of building construction and to carry out machinery installation at a nuclear power station.

The efficacy of digital models in helping overcome technical, procedural, and organisational challenges has been investigated across the project life cycle (see (Staub-French & Fischer, 2007; Staub-French & Khanzode, 2007; Aranda-Mena et al., 2009; Kunz & Fischer, 2009)). For instance, multi-disciplinary project teams used 3D CAD models linked to existing software solutions to design, coordinate, estimate, plan, schedule and manage a biotechnology plant construction project (Staub-French & Fischer, 2007). Staub-French & Khanzode (Staub-French & Khanzode, 2007), studied two projects that were using 3D and 4D modelling tools, and provided guidelines for overcoming the technical, procedural and organisational challenges associated with implementing these technologies.

On the other hand, in a multiple case study focusing mainly on the work of architectural and engineering consultants, contractors and steel fabricators, Aranda-Mena et al. (2009) found that BIM enhanced technical, operational and business capabilities across the project life cycle. Kunz & Fischer (2009) found that multi-disciplinary use of integrated 3D/4D models throughout the project life cycle, also known as virtual design and construction (VDC), consistently improved business performance. Staub-French & Fischer (2007, p. 212) also found that visualisation and communication capabilities of the tools were their most useful functionality, and the use of visual product modelling tools that most stakeholders can understand, such as CAD, visual organization models, and 4D schedule animations has also been emphasised (Kunz & Fischer, 2009). Indeed, it has been argued that only visual models have the power to support collaboration “by a broad class of stakeholders” (Kunz & Fischer, 2009, p. 37).

Lastly, two industry reports (Young Jr. et al., 2008; Young Jr. et al., 2009) demonstrated how BIM was being applied across the project lifecycle from design to site excavation and energy analysis. Participants across the project life cycle – architects (58%), contractors (71%), and owners (70%) - reported positive benefits of using BIM, with the exception of engineers who reported the least benefit (48%) in terms of sufficient functionality and return on investment (Young Jr. et al., 2009, p. 7). It was suggested that increasing the technology offerings for engineers may address the latter
perception. One thing that is clear from the literature is that BIM has enabled significant changes to the work practices of design professionals, although there are, at times, divergent accounts as to how in some of the studies. An example of the latter is discussed in the more detailed discussion of implementations in section 2.3.

2.1.3 Teams and networks
The literature also discusses integration with a broader focus on how teams and organisational networks are supported by digital tools, rather than on the kind of work done, by which disciplines or at which stages of the project. It focuses on the interactive, communicative and inter-organisational aspects of project work (Bellamy et al., 2005; Fox & Hietanen, 2007; Hartmann & Fischer, 2007), building information modelling practice paradigms in project networks (Taylor & Bernstein, 2009) and socialization and coordination among virtual teams from diverse backgrounds (Schroepfer, 2006; El-Tayeh & Gil, 2007). Findings suggest that features of computer supported cooperative work (CSCW) can be usefully integrated with BIM to support socialisation among virtual project teams (El-Tayeh & Gil, 2007). An extranet used by one organisation was not found to support socialisation across organisational boundaries due to limitations posed by professional liability issues (El-Tayeh & Gil, 2007), although a recent report found that such concerns seem to be fading as the legal framework for BIM is developing (Young Jr. et al., 2009, p. 5). Furthermore, it has been argued that the rising numbers of digitally native young professionals coming into the industry and the increased outsourcing of work to AEC professionals across the globe due to competition and scarcity of resources is likely to result in the increased "use of digital media to support problem-solving across virtual AEC project teams" (El-Tayeh & Gil, 2007, p. 465).

Bellamy et al.'s (2005) industry-based research examined communication among both co-located and virtual teams involved in the activity of designing. Using evidence based on data collected from a multi-national firm with multiple offices in different countries, they indicate that there is an unavoidable move from traditional co-located to virtual working environments particularly in international projects. This comes with changes in the nature of the interaction process between design professionals. For instance, the virtual team interacting using an electronic white board, asked proportionately more questions using the "Asks Orientation" category of interaction (i.e., information, repetition, confirmation) than the co-located team, which used a more spontaneous, "Gives Suggestion" interaction category (i.e., giving direction, implying autonomy for other) (Bellamy et al., 2005, p. 359). Similarly, in a case study of a major high speed rail project, seeking clarification was found to take up 30-40% more time in virtual interactions than when participants interacted physically (Schroepfer, 2006, p. 73).

Whyte et al. (2007) suggest that in order for practitioners to enhance their performance they should reflect on the pace and style of their interaction as well as the types of media they use. These at different moments, may be "unfrozen" or "refrozen" (Whyte et al., 2007, p. 26), thereby either "opening up areas of design for negotiation by particular parties or closing down debate" respectively. Hence, it is vital that AEC professionals are familiar with the different environments in which they have to work in and are equipped with the necessary skills they need. More so in virtual environments, where the use of digital technologies is more intense (Schroepfer, 2006, p. 75), the
need to understand and develop core generic skills such as communication of design, technical concepts and information becomes crucial to the effective use of these technologies.

Fox & Hietanen (2007) conducted a field study of 20 organisations that are in “the use stage” of diffusing BIM innovation, while Taylor & Bernstein (2009) also investigated 26 specific cases of firms using BIM tools. The latter research highlights the importance of understanding and developing inter-organizational work practices to reap the benefits of building information modelling, identifying four emergent practice paradigms; visualisation, coordination, analysis, and supply chain integration. Based on Mooney et al.’s (1996) framework for assessing the business value of information technology, Fox & Hietanen (2007) revealed that the inter-organisational use of BIMs can enable three types of effects; automational, informational, and transformational effects.

A move towards a transformational effect is supported by Taylor & Bernstein’s (2009) findings, which showed how the organisations they studied evolved from one of four practice paradigms (visualisation, analysis, coordination, and supply chain integration paradigms) to another in subsequent projects. All but two of the 20 organisations studied had evolved from the visualisation paradigm. The research concluded that inter-organisational practices “evolve as BIM practice paradigms evolve” (Taylor & Bernstein, 2009, p. 75). The interactive, communicative and inter-organisational theme is further reflected in a study of the Fulton Street Transit Center (FSTC) project in New York City by Hartmann & Fischer (2007). They analysed how the project management team used 3D/4D models to communicate the project-generated knowledge to other participants or stakeholders that are non-engineers or non-project managers to support the constructability review process.

2.2 Interoperability:

In the construction literature, interoperability has been discussed from a variety of perspectives both technical and non-technical, but mostly the former. From a technical perspective, interoperability has been described simply as “the ability to manage and communicate electronic product and project data among collaborating firms” (Young Jr., Jones, & Bernstein, 2007, p. 4). In concurrent engineering (an approach similar to IPD), interoperability is seen as the primary mechanism through which all technologies and tools utilised in the project development process are integrated (Kamara, Anumba, & Cutting-Decelle, 2007, p. 2). To ensure seamless information exchange between otherwise incompatible entities, a standards-based approach to achieving technical (or systems) interoperability may be adopted, although usually in combination with other approaches such as the “semantic interoperability” and “software engineering” approaches (Pouchard & Cutting-Decelle, 2007, p. 121).

2.2.1 Standardisation

Despite many proposals to represent standardised data models and services, interoperability is still a problem in the AEC industry (Grilo & Jardim-Goncalves, 2010; Shen et al., 2010), from the project life cycle to operations and maintenance. The latter authors attribute this to the many heterogeneous
applications and systems in use as well as the dynamism and adaptability essential to operating in the industry. Bakis, Aouad, & Kagioglou (2007) on the other hand, argue that it is a result of the impossibility of developing a single building model that caters for all areas of construction. As such different standards for interoperability target different segments of the AEC industry, with no common methodology for managing information exchange. For instance, although the Industry Foundation Class (IFC) standard (IFC 2x3) is applicable to several construction disciplines (Bakis et al., 2007, p. 587), it is used mainly by architects to exchange conceptual and detail design information with other participants (Shen et al., 2010).

CIMSteel standard (CIS/2) is used by structural engineers to exchange design, analysis and detailing information about steel frames (Shen et al., 2010) while STEP (Standard for the Exchange of Product Model Data), which is among the earliest and most important standards (Bakis et al., 2007), caters for many aspects of engineering and construction including the representation of 3D models (part 225 of STEP). ISO 15926 can, in theory, be used for the entire lifecycle of a facility (Shen et al., 2010). However, despite this heterogeneity, Grilo & Jardim-Goncalves (2010) argue that technical interoperability is not the problem for AEC in implementing BIM, as it has been shown to be feasible. Rather, understanding and determining the value of such interoperability to the business, in essence making a case for a broader definition of interoperability is the issue. This will be returned to later in the section. Suffice it to say here, that the advent of BIM has brought sharper focus on the problems of interoperability. According to Young Jr. et al. (2007), the promise of improved interoperability is among the factors with the greatest influence (at 41%) on the decision to use BIM. Howard & Björk (2008), in a qualitative study of industry experts, focused on the feasibility of BIM, the conditions necessary for its success, and the role of formal standards, particularly the IFCs, which though too complex, are seen as the most popular. Cerovsek (2010) also analysed the development, implementation, and use of the BIM schema from the standpoint of standardisation, by critically reviewing the features of over 150 tools and digital models in use in the industry.

### 2.2.2 Interfaces and linkages

Another theme in the literature is related to what may be described as interfaces or linkages. Shen et al. (2010), in a review of systems integration and collaboration in the AEC/FM industry, refers to such interfaces and linkages as frameworks interoperability. This focuses on “common communication languages and protocols” (Shen et al., 2010, p. 198), which allow different systems or sub-systems to use different data models and formats. Shen et al. (2010) argue that frameworks interoperability is more suitable for distributed and loosely coupled integration environments, which arguably, many major construction projects are. Technologies for achieving frameworks interoperability include commercially available Web-based systems which are being used in the industry, as well as the (intelligent) agent-based systems which they can be implemented as, although as yet, there is little evidence of the latter’s implementation in actual projects (Shen et al., 2010). Since the development and deployment of the three major distributed object standards, “CORBA by the Object Management Group (OMG), COM/DCOM by Microsoft and Java RMI” (Shen et al., 2010, p. 199), distributed object technologies have become more widely used for systems integration. It has also been argued that XML and its Web Services related technologies can be used as an alternative to distributed object-based technologies in developing a distributed product data
sharing design environment (Bakis et al., 2007, p. 590). However, there is little evidence of such use in actual projects (Bakis et al., 2007), although Babic et al. (2010) reported on a project that implemented BIM (using the IFC standard) as a link between an enterprise resource planning (ERP) information system that supports manufacturing process and construction object related information, mainly handled by CAD tools. Similarly, Staub-French & Fischer showed how 3D CAD models were linked to cost estimates and schedules to design, coordinate, estimate, plan, schedule and manage a biotechnology project.

2.2.3 Non-technical interoperability
As noted earlier, there are other perspectives on interoperability beyond the usual technical perspective. For instance, Pouchard & Cutting-Decelle (2007) discussed, albeit briefly, human, inter-community and legal interoperability. Others, however, have studied the cultural (Young Jr. et al., 2007) and business level (Grilo & Jardim-Goncalves, 2010) perspectives in more detail. For the former, interoperability is “the ability to implement and manage collaborative relationships among cross-disciplinary build teams that enables integrated project execution” (Young Jr. et al., 2007, p. 4). The latter, on the other hand, made an argument for understanding and estimating the value of interoperability to the business in terms of efficiency, differentiation and competitiveness. Industry studies have also measured BIM user perspectives (Young Jr. et al., 2008) on the developing elements of a BIM infrastructure, including, inevitably, the development of standards. A variety of perspectives on the current status and importance of interoperability in the North American construction market were also explored by Young Jr. et al. (2007). Edum-Fotwe, Gibb, & Benforde-Miller (2004) showed how one organisation resolved the problems arising from its adoption of an apparently contradictory agenda of standardisation and innovation.

2.3 Actual practices:

The previous section described the major themes around implementation of digital technologies in the major projects investigated in the literature. This section discusses how some of the technologies (mainly BIM) have been actually implemented and their major benefits, the main problems faced and how they were addressed, and the green design practices that they enabled.

2.3.1 Implementations and benefits
From the discussion in the previous section, it can be seen that the integration of disciplines, stages and technical systems is a general goal in major projects but that there is also a diversity of implementation areas of digital technologies and the benefits reported, from one project to another and even within projects. Digital technologies have been described as “digital infrastructure” for delivery, a term which reflects their use as “nested sets of objects associated with coordination of knowledge across multiple knowledge boundaries in the delivery of projects”, rather than simply as distinct objects (Whyte & Lobo, 2010, p. 564). Babic et al. (2010) reports on a study that focused on project progress monitoring and material flow management, while Bendixen & Koch (2007) following three building projects over a year, investigated the role of visualisation practices in the
briefing and design process. Although the latter’s main focus was not on technologies, they provide an interesting example of how digital tools (mainly CAD drawings) were used for political purposes during the briefing phase. Through a few CAD operations, changes could be made to the drawing to influence potential sponsors, even without the input of other engineering expertise.

Khanzode et al. (2005, p. 146) also argued that rapid iterations using 3D & 4D solutions enabled efficient decision making in the early (conceptual) design phase of a project. Bendixen & Koch (2007) conclude that communitarian management approaches (Knorr Cetina, 1999) should be chosen to promote innovative briefing and design. In one study, only the main building elements were included in the BIM model in order to simplify its introduction process, while other supporting material and elements were linked via external references and generally handled by an ERP system (Babic et al., 2010, p. 543). However, while it helped in integrating the two systems, BIM in this study was used in a limited (internal) environment. The implementation of BIM in an external environment and with more wide-ranging benefits was reported in the results of a multiple-case study carried out in Australia and Hong Kong (Aranda-Mena et al., 2009). The main criterion for selection of cases was that they had to be collaborating by sharing BIM data between two or more consultants/stakeholders. The results of the case studies were cross-analysed, based on which the authors identified clear and measurable outcomes, namely, technical, operational and business capabilities enabled through BIM. A detailed discussion of these outcomes is not possible due to space limitations so a few examples would suffice. These include the ability to produce necessary drawings and documentation from the BIM model (technical outcome), ability to design in a 3D environment throughout the entire design process (operational outcome) and reduced risks associated with information-related errors (business outcome). Furthermore, the authors believe that despite the initial high cost of BIM, by fully implementing these capabilities, it is expected “that organisations will recover rapidly and their performance will drastically improve” (Aranda-Mena et al., 2009, p. 432).

Several implementations were reported in studies conducted by researchers at Stanford University (Koo & Fischer, 2000; Fischer & Haymaker, 2001; Fischer, Haymaker, & Liston, 2003; Khanzode et al., 2005; Staub-French & Fischer, 2007; Staub-French & Khanzode, 2007). For instance, Fischer & Haymaker (2001) and Fischer et al. (2003) investigated actual implementations and reported the benefits of applying 3D and 4D models for various stages and stakeholders in the project and asset lifecycle. These were, however, more focused on model use in the project phases – in one study, the conceptual design or Lean design phase (Khanzode et al., 2005) - and less on, for instance, how these models are used in operations, a problem of reuse of project information alluded to recently by Li, Lu, & Huang (2009, p. 369). Nevertheless, the results indicate that 4D models supported constructability and schedule analyses well and are effective tools to communicate schedule and scope information in the project phases (Fischer & Haymaker, 2001). But while clients have generally used the models to verify constructability prior to contract award, general contractors applied 4D models in more varied ways.

In addition to communicating scope and schedule information to subcontractors and other parties, they are also used for overall and detailed construction planning, testing constructability of design and executability of schedule before committing resources to the field (Fischer et al., 2003) among
many other observed benefits. Koo & Fischer (2000), had in an earlier study investigating the effectiveness of 4D models in conveying a construction schedule, found that the models are a useful alternative to project scheduling tools like CPM networks and bar charts. At least 12 other specific benefits were reported by Staub-French & Fischer (2007) in a study in which members of the research team actively participated in, observed and documented the activities of the construction project team for a biotechnology plant. Underlying these benefits, is the commitment that each team member made to modelling their respective scope of work in 3D CAD using a design-build, concurrent engineering (CE) approach, before the start of design and construction. The authors believe that this early commitment and simultaneous involvement of the project team coupled with the use of shared 3D and 4D models played a significant role in allowing the team to deliver a superior facility in less time, at lower cost and with less hassle.

Other studies have surveyed industry participants on the perceived benefits or value of BIM in construction projects (Young Jr. et al., 2008; Suermann & Issa, 2009; Young Jr. et al., 2009). Perceptions of knowledgeable users were sought on issues ranging from the impact of BIM on the construction industry’s key performance indicators (Suermann & Issa, 2009), to its adoption, implementation, value and impact within firms (Young Jr. et al., 2008). User perceptions were also sought on ROI (Young Jr. et al., 2009), the tracking of which remains a tricky proposition as argued by the authors, but more will be said about this in section 4.4.2 on problems and challenges. User perspectives were also sought on the developing elements of a BIM infrastructure such as standards, content, software, training and certification, as well as on the use of BIM on green projects (Young Jr. et al., 2008). Suermann & Issa’s (2009) findings indicate that implementing BIM improves all six industry key performance indicators (KPIs) of quality control, on-time completion, cost, safety, dollar/unit, and units/man-hour to varying degrees, while Young Jr. et al. (2009) argue that the vast majority of users are experiencing benefits directly attributable to BIM both in terms of qualitative process improvements (e.g., reduction in rework enabled by early coordination, improved scheduling through 4D simulation) and enhanced project outcomes.

Although architects are perceived to experience the most value (Young Jr. et al., 2009, p. 28), findings from surveys and multiple case studies demonstrate that BIM generates value across the disciplines and in a wide variety of project types and activities from site excavation to energy analysis (Young Jr. et al., 2008; Young Jr. et al., 2009). The sometimes divergent findings, however, may not be unrelated to the level of maturity of BIM, the diversity of areas and methods of its application and the research methods used. For instance, while Young Jr. et al. (2008, p. 7) argue that one of the key benefits of BIM is in allowing designers to spend less time drafting and more time designing, elsewhere, findings of two implementation case studies suggested more benefit when designers focus less on detailed design and “more on the overall design and coordination of design tasks” (Staub-French & Khanzode, 2007, p. 406).

Finally, in view of the topicality of technology use in projects and the potential implications on project practices, some of the studies offer implementation guidelines, from assigning responsibility for creating models and pre-qualifying team members based on 3D authoring skills (Khanzode et al., 2005), to making extensive use of the technology environment, development of and adherence to common rules, and the controlled introduction of the tool(s) and provision of user support (Karlsson
et al., 2008). Others focus on overcoming technical, procedural and organisational challenges often associated with implementing 3D and 4D technologies (Staub-French & Khanzode, 2007), the suitability of particular tools, and the coordination of team members from different national, cultural, and organizational backgrounds over multiple time zones (Schroepfer, 2006). For instance, Staub-French & Khanzode (2007), in a case study of two projects (a biotechnology plant and a three-storey medical office building), provided guidelines, such as bringing teams together early in the project, developing new skills and designers focusing on overall design and coordination and less on detailed design. Specific benefits reported include “increased productivity, elimination of field interferences, increased pre-fabrication, less rework, fewer requests for information, fewer change orders, less cost growth, and a decrease in time from start of construction to facility turnover” (Staub-French & Khanzode, 2007, p. 406).

These efficiencies were, however, not achieved without some compromise, mainly in relation to the increased time required for design, design planning, coordination, estimation, and the increase in the associated costs. However, in several case studies, administrative and other cost savings (up to $10 million in one project) were often greater than the associated costs of using BIM (Young Jr. et al., 2009). For instance, despite significant time spent on planning, one case study not only turned out to be “the fastest designed large-scale health care project [in California], it was done at no added cost and resulted in higher-quality and better coordinated deliverables” (Young Jr. et al., 2009, p. 25).

In another case study, a four-month hiatus in the project due to a funding and scope review, enabled the designer to amend the contract and convert the CAD design to BIM, which suggests that despite the emphasis on early decision-making and organising around BIM, it is never too late to adopt it (Young Jr. et al., 2009, p. 43).

2.3.2 Problems and challenges

An analysis of the problems and challenges reported in the literature indicates a number of salient issues beyond the oft-repeated problems of coordination, cost, increased time/effort in creating 3D models, resource requirements, etc., that have been evident in the review thus far. The more salient and interesting examples include the constraints occasioned by the technology being implemented, organisational issues (specifically relating to leadership), information-related risks, problems of training, and accurate measurement of value. These are discussed in what follows.

Technology limitations: The importance of paying analytic attention to a technology’s material constraints and affordances, rather than only showing how people organize around the technologies they employ, has been emphasised by Leonardi & Barley (2008, p. 163). In implementing innovative technologies, projects may come face-to-face with the limitations of the technologies, e.g., the BIM software (Goedert & Meadati, 2008) or incongruities between the goals of innovation and the need for standardisation (Kondo, 2000; Edum-Fotwe et al., 2004). Standardisation is necessary for consistency and wide deployment of a technology, but may also breed rigid structures, which could be inimical to innovation (Edum-Fotwe et al., 2004). To resolve this problem, a central standardisation database (CSD) was used in a major hospital project that turned out to be the fastest build of a hospital of its size in the UK (Edum-Fotwe et al., 2004, p. 371). This enabled architects and design engineers to exercise their design freedom but at the same time submit completed designs
and details of processes for each project for review by the centre, to ensure conformity to standards and guidelines, as well as to update the database with changes in the technology and developments in the sector as a whole.

In contrast, a BIM software that was useful in the pre-construction phases of another project, was found to be not specifically prepared to capture construction process documentation, which necessitated not only modifications to the software but to procedures as well (Goedert & Meadati, 2008). These modifications included using laser scanning technology to collect 3D as-built geometric information, the linking of the 3D as-built model with the actual construction schedule to generate a 4D as-constructed model, and additional software programming to create a query capable of a 4D display (Goedert & Meadati, 2008). Similarly, in a landmark study of two major projects that implemented emerging 3D and 4D technologies, Staub-French & Khanzode (2007) reported limitations pertaining to the effort required to set up the CAD and schedule models, the ability of 4D tools to deal with frequent design and schedule changes, and the lack of automated analysis of 4D models.

**Leadership:** This was found to be a challenge in some projects (Aranda-Mena et al., 2009; Dossick & Neff, 2010b). While BIM makes the connections among project members more visible, competing obligations to project, scope and company were often found to be at odds with project goals and BIM-supported collaboration (p.463). To overcome these, the projects relied on strong individual leadership (i.e., of the respective disciplines) to hold the people together and inspire collaboration (p.466). Similarly, the problem of interoperability has often been resolved by simply adopting the same technology throughout the project. This requires leadership, which Li et al. (2009) found in several case studies, is often provided by the client adopting a software package and contractors getting the same to maintain compatibility (p.370). However, Frank Gehry’s example in Yoo et al. (2006), suggests that power relations may ultimately decide who provides this leadership, which, in this case, was the architect.

**Information risks:** Information-related risks and problems have been reported in several studies as hindering, potentially or actually, the implementation of BIM tools (Young Jr. et al., 2008; Aranda-Mena et al., 2009). Aranda-Mena (2009), through five in-depth case studies of small, medium and large architectural and engineering practices, identified inhibitors towards the uptake of BIM. The studies focused mainly on challenges and benefits for architectural and engineering consultants, contractors and steel fabricators. The use of BIM authoring tools was the main focus of analysis and the authors identified risks associated with ownership of information, IP, payment for information and problems related to legal frameworks. Young Jr. et al., (2008) report similar information-related risks and liabilities in their study, although these were mainly the concerns of clients, architects, and engineers, rather than actual problems faced during projects. These include concerns (in varying degrees between the groups) over errors and accuracy, liability and legal issues, and who takes ownership of the model after distribution and takes responsibility for changes made by others (Young Jr. et al., 2008, p. 33). Fischer et al. (Fischer et al., 2003) had also reported information-related problems in a study of the use of 3D and 4D models on a major project. These include inconsistencies and lack of data (related to geometry and scheduling or the link between the latter
two), and in some instances, too little detail in the 3D model, or too much data "which slows down computational processing of the 3D and 4D models" (Fischer et al., 2003, p. 25).

Furthermore, the shelf life of 4D information is limited (Staub-French & Khanzode, 2007). Since activities are usually broken down daily or over a few days, a 4D model would only be useful to work crews if it is continuously updated. This means updating it daily which, as found in a study of two major construction projects, was a challenging, yet crucial task in representing as-built conditions as well as activities to be carried out during the week (Staub-French & Khanzode, 2007, p. 404). It is evident that the immediate consequence and resolution of the problems reported by (Fischer et al., 2003) and (Staub-French & Khanzode, 2007) was often the additional time and resources needed to model the required information. However, it was not evident whether these problems aggravated, or heightened concern over, information risks among the various project participants, although it can be argued that they have the potential and as such, need to be given due consideration. Perhaps aptly, one of the benefits of the [4D] modelling process, according to Fischer et al.(2003, p. 24), is that it "makes it very clear where complete scope and schedule information exists and where additional thinking is needed".

Training: The need for trained people with the skills necessary to implement the types of technologies (mostly 3D tools) is often cited in the literature (Bibby et al., 2006; Staub-French & Khanzode, 2007; Post, 2008; Young Jr. et al., 2008). However, trained people are scarce, as discovered in Aranda-Mena et al.’s study (2009). Therefore, for some project participants, e.g., subcontractors, who may not have the skills available in-house, recruiting experts (e.g., 3D modellers) into the project, may be difficult, even if they had the resources. Effective tool use may therefore suffer in some aspects/stages of the project and the challenge of providing requisite training could mean that the less killed participants are always trying to keep up with the more skilled players in the project. On the other hand, however, the use of 3D tools, which requires skilled personnel in one stage, e.g., design, makes it possible for less-skilled labour to be used in another stage that would normally require skilled interpretation of drawings, e.g., installation of MEP systems. Staub-French & Khanzode (2007, p. 396) report that in one of the two projects they studied, 3D/4D tools made it possible for less-skilled labour “to bolt together systems which would normally require experienced plumbers”, without reducing the quality of the installation.

Young Jr. et al., (2008) identified concerns over inexperience of end users and their learning curves but found variations in preferred solutions between clients, architects, engineers, contractors, and beginners and small firms. While architects are more likely to bring in external trainers, engineers are most likely to be self-taught, and contractors are most likely to train in-house. Some clients (one in ten) outsource BIM completely, and therefore, don’t need training (Young Jr. et al., 2008). Finally, a solution “to quicken the BIM learning curve” as suggested by the authors, “is for firms to encourage colleges and universities to train students in BIM tools and to recruit ready-made BIM experts when the students graduate” (Young Jr. et al., 2008, p. 40).

Measurement: Young Jr. et al. (2009) reported six in-depth case studies that showed how BIM is solving real problems on actual projects. However, a problem frequently faced is that of measurement of value or benefit, e.g., of ROI and actual cost savings, which the authors described as
tricky (Young Jr. et al., 2009, p. 8). In view of the variability and uniqueness of projects, obtaining data for making comparisons is difficult. Furthermore, Li et al. (2009, p. 370) in their research, discovered that despite anecdotal evidence of its success, virtual design and construction (VDC) was better implemented in areas where benefits could be tangibly measured, e.g., clash detection or construction flow for a typical floor, than in those where measurements are more difficult or not possible. For instance, getting data on “exact dollar values with change orders, schedule and productivity” is difficult because every hour of labour has to be mapped accurately, but “everyone protects their production rates” (Young Jr. et al., 2009, p. 11). Currently, about half of projects surveyed track ROI as part of internal BIM implementation processes but the authors argue that “as more industry-standard metrics are developed, the ability to track ROI could improve in the coming years” (Young Jr. et al., 2009, p. 8).

2.3.3 Green project practices

According to Bernstein (2007, p. 26), “the AEC industry is now paying particular attention to how the buildings of the future are designed, constructed and operated”. However, a review of the literature and survey of construction professionals found that although the industry is taking some account of sustainability issues, there is still more that needs to be done (Pitt et al., 2009). A more recent study (Li et al., 2011) also involved a literature review and survey of industry professionals including those that have participated in Green Mark certified projects. It highlighted the critical role of “advanced machinery and equipment” and “effective and efficient software” in injecting “environmentally friendly features into projects” that will lead to Green Mark certification (Li et al., 2011, p. 25).

A rather surprising finding of this review, therefore, is that green design issues seem to be under-represented in studies of actual BIM or other digital technology use in construction projects. The few studies that focused on sustainability issues were often proposals rather than investigations conducted in the context of actual project implementations. For instance, Zhou, Bo, & Qian (2009) put forward a proposal for integrating BIM technology with other green tools (e.g., LEED and energy analysis software) for green design, construction and even operations, while Zhu (2010) suggests that BIM can provide a “complete digital expression for sustainable design”. Furthermore, while a link has been made between lean construction principles and green practices (Lapinski, Horman, & Riley, 2006) and between lean principles and 3D/4D CAD (Khanzode et al., 2005) or BIM (Sacks et al., 2010). However, no link could be found in the literature that integrates lean, green and BIM in actual projects, which could have discovered the kind of synergies suggested by Sacks et al. (2010).

Nonetheless, a recent study by Mah et al. (2011), conducted in a real housing project, showed how BIM can be implemented in sustainable construction practice. It investigated the integration of BIM with an intelligent database which permits “end-users to calculate CO2 emissions for different styles of houses with different types of construction methodology” (Mah et al., 2011, p. 176). Based on logical rules and model constraints, the model allows for the instant determination of the emissions produced per assembly (Mah et al., 2011, p. 175).
Another (industry) study involving a survey and case studies specifically discussed the role of BIM in green design and construction practices, finding “significant opportunities” for such tools (Young Jr. et al., 2008). These include helping in analysing “the performance of a building, including such green aspects as daylighting, energy efficiency and sustainable materials” (Young Jr. et al., 2008, p. 5). The report also found that “most BIM users are frequently involved in green projects and find BIM to be helpful with those projects” (Young Jr. et al., 2008, p. 5). In one of the case studies, the unusual involvement of the performance analysis team of a design and engineering firm early on (at the schematic phase), enabled them to influence and/or give feedback on key design decisions and alternatives, by using “software that exchanged nearly all data seamlessly with the BIM” (Young Jr. et al., 2008, p. 20). This led them closer to that clearly defined target (LEED certification) and resulted in other improved outcomes, e.g., better communication, “reduced need for re-entering data between software applications, and the ability to avoid many costly redesigns late in the schedule” (Young Jr. et al., 2008, p. 20).

The paucity of research evidence may also not be unconnected with the level of maturity of BIM in the industry. For instance, user experience of BIM on green “sustainable” projects suggests that expert users are twice as likely to see it as helpful on green projects compared to beginners (Young Jr. et al., 2008, p. 3). However, even with inexperienced users, this lack of appreciation may be mitigated by a commitment to sustainable design, as in the case of the design and engineering firm mentioned above, which tied the opportunity to “implement a fully-integrated BIM strategy for the first time” on a project, with its “goal of achieving LEED certification” (Young Jr. et al., 2008, p. 20).

3 Discussion and conclusion:

3.1 Theorised phenomena

Researchers have explored the use of digital technologies in the AEC disciplines and described quite similar or complementary paths or “trajectories” (Taylor & Bernstein, 2009) that characterise their development and use. These include the four BIM paradigm trajectories of visualization, coordination, analysis, and supply chain integration earlier mentioned (Taylor & Bernstein, 2009), the three stages of VDC development - visualisation, integration, and automation (Fischer, 2006), and Fox & Hietanen’s (2007) discussion of the automational, informational, and transformational priorities to which BIM has been applied in diverse projects. These trajectories, in the most part, appear to evolve cumulatively, with visualisation being the initial or most immediate, and aspects of the others co-evolving to varying degrees from one project to another and as firms’ experience with BIM and other digital technologies matures. Furthermore, the evidence (Fox & Hietanen, 2007; Taylor & Bernstein, 2009) suggests that it is only when these technologies evolve to support inter-organisational work practices that truly transformational benefits are realised.

Similarly, it can be argued that the three views of design management (Khanzode et al., 2005), namely the conversion, flow, and value views, are closely related to the trajectories identified above. These views may be holistically integrated through the use of 3D/4D CAD tools in combination with other principles, such as Lean construction. So visualisation, the creation of continuous
information/work flow, and value generation through minimising waste are inbuilt in the 3D/4D CAD-enabled processes of coordination, constructability analyses, and scheduling among others described by Khanzode et al. (2005).

It is worth mentioning, however, that of all the interrelated and complementary trajectories identified, the automational phase appears to be the least developed, although not for want of research. For instance, when 3D models are shared between designers, structural engineers, and fabricators, the need for someone to physically convert the data from design to production details is eliminated, as this can be done automatically (Fox & Hietanen, 2007). However, with a few exceptions, (Heikkilä & Jaakkola’s (2003) description of an automated 3D blade control system for a road grader is one), there is scant evidence in the literature of the kind of automation that enables completion of work as is the case in, for instance, the automobile industry, where robots can process digital information and handle whole sections of assembly with little intervention from humans. Arguably, this is as a result of the nature of construction work where, according to Dossick & Neff (2010a, p. 12), “tasks may need the fuzziness of free association and the juxtaposition of seemingly unrelated things to generate new ideas and innovation or collective problem solving that the current BIM interfaces do not provide”.

Digital technologies used in major construction and infrastructure projects have been severally described as boundary objects (Gal, Lytinen, & Yoo, 2008; Whyte & Lobo, 2010), tightly coupled (Yoo et al., 2006) and clean technology (Dossick & Neff, 2010a). The term boundary object was first used by Star & Griesemer (1989) and, subsequently, Knorr-Cetina (1999) to describe objects that are used to create knowledge and understanding at the boundaries of different scientific, professional, organisational and social worlds. According to Star & Griesemer (1989, p. 393), they are concrete or abstract objects “which are both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. Gal et al. (2008) in a case study of a major US general contractor, found that boundary objects (3D technologies) are intricately intertwined with organisational practices and organisational identities such that changes in the former usually bring about changes in the latter two. Changes in organisational identity were reflected in changing tasks, roles, and interactions across different projects, while changes in organisational practices occurred in standardised practices and modes of communication. Notably, the changes as well as the power dynamics at play became apparent when the architectural firm on a project introduced 3D technology and was able to enforce its adoption by other participating firms (Yoo et al., 2006; Gal et al., 2008).

Conceptualising digital technologies used in design and construction as boundary objects has not been without criticism, however. Whyte & Lobo (2010) argued that it often focuses attention more on individual technologies than on the connections between various technologies used in a typical project; on the soft interactions and knowledge sharing they enable than on the standardised coordination practices that emerge around them. They could, therefore, be more usefully conceptualised as part of a digital infrastructure for project delivery (Whyte & Lobo, 2010). BIM has also been described as clean technology, partly in reference to the “explicit processes and standards required for sharing digital information” and because technology-mediated exchange is seen as more reliable and less error-prone than human-only communication (Dossick & Neff, 2010a, p. 4).
Thus it is seen as not entirely consistent with “messy talk”, the “unplanned, unforeseen and unanticipated” (Dossick & Neff, 2010a, p. 3) dialogue that is inherent in, and necessary for conversation and problem solving in formal collaboration processes. However, it is seen to have the potential to enable the creation of knowledge repositories that are readily accessible, shared and understood by people from diverse disciplinary and conceptual persuasions (Dossick & Neff, 2010a). As digital infrastructure for project delivery, technologies such as BIM result in a form of organising that “involves prescribed processes, stage-gates and top-down, hierarchical forms of sign-off and control rather than networks with distributed non-hierarchical, relational forms of organising” (Whyte & Lobo, 2010, p. 565). Conceptualising BIM this way, it may be argued, would help practitioners reflectively improve their practices (Whyte & Lobo, 2010), and perhaps, ultimately, reconcile the nature of messy talk with clean technologies.

3.2 Synthesis (summary of main findings)

An integrated approach to project delivery is meant to reconcile the range of disciplines, complex interactions, and technical systems at different stages of a major project. The diversity of approaches to achieve this reconciliation means that as yet, no clear, standard approach has been established. Although BIM appears to be the emerging leading paradigm, integrated digital technologies have been implemented in major projects with nomenclatures such as Concurrent Engineering (CE) (Staub-French & Fischer, 2007), Virtual Design and Construction (VDC) (Kunz & Fischer, 2009; Li et al., 2009) and Construction Virtual Prototyping (CVP) (Huang et al., 2009). Nonetheless, from the evidence reviewed, two main characteristics may be discerned as dominant among the projects. Firstly, instead of a truly integrated approach, projects have used digital technologies to achieve only partial integration, i.e., of some stages, disciplines, or teams in the project or asset lifecycle. Indeed, according to Hartmann et al. (2008), many projects have applied these technologies (mainly 3D/4D models) in only one application area and in only one project phase. In the case of BIM, this has been attributed to the complexity of existing software solutions which means it may need to be applied in limited areas initially (Howard & Björk, 2008). The use of technologies to integrate the asset/facilities management discipline with other disciplines during the project is least evident in the literature. While this may well be for the reason mentioned above, it may also not be unconnected with project procurement arrangements, as the facilities management team would not often be known in advance in many types of contracts.

Secondly, many digital technologies may be used primarily as creative tools (e.g., 3D CAD applications used for modelling and visualisation). However, the evidence suggests that they are rarely used in isolation. Rather, they are frequently deployed alongside other technologies with a focus on supporting communication, coordination, and collaboration tasks among co-located or virtual teams e.g., (Bellamy et al., 2005; Schroepfer, 2006; Fox & Hietanen, 2007; Hartmann & Fischer, 2007) or more broadly across project networks, e.g., (Taylor & Bernstein, 2009). In one study, a digital prototype was developed and subsequently tested in a real project environment to support socialization among virtual engineering design teams (El-Tayeh & Gil, 2007). Initially encouraging results in this case, were, however, overshadowed by concerns over professional liability. Nevertheless, the majority of the evidence supports the positive effect of digital
technologies on inter- and intra-group interaction. For instance, as mentioned earlier, it has been shown that the inter-organisational use of BIM can lead to automational, informational, and transformational effects (Fox & Hietanen, 2007), while Taylor & Bernstein found that inter-organisational information sharing practices co-evolved alongside the BIM practice paradigm adopted.

Interoperability is a perennial problem of digital technology innovations and implementations in the construction industry. Based on the studies reviewed, it appears that this problem partly stems from the diversity of applications and systems used in projects and the need for dynamism and adaptability in the industry (Grilo & Jardim-Goncalves, 2010; Shen et al., 2010). It may also partly be attributed to the narrow (technical) definition of interoperability, even though there is a scope for broadening it to include business and cultural level elements, as suggested by Young Jr. et al. (2007) and Grilo & Jardim-Goncalves (2010). To ensure seamless information exchange between otherwise incompatible entities, a standards-based approach to achieving systems interoperability may be adopted, usually in combination with other approaches such as the “semantic interoperability” and “software engineering” approaches (Pouchard & Cutting-Decelle, 2007, p. 121). However, despite many proposals to represent standardised data models and services, interoperability is still a problem in the industry (Grilo & Jardim-Goncalves, 2010; Shen et al., 2010), some of the reasons for which have been mentioned above. Reflecting the difficulty of addressing this problem, Bakis, Aouad, & Kagioglou (2007) argued that it is virtually impossible to develop a single building model that caters for all areas of construction, which means that different standards for interoperability target different segments of the industry, with no common methodology for managing information exchange. The feasibility of BIM as such a common methodology has been discussed (Howard & Björk, 2008; Cerovsek, 2010). However, Grilo & Jardim-Goncalves (2010), argue that technical interoperability is not the problem for the industry in implementing BIM, but understanding and determining the value of such interoperability to the business, re-echoing Pouchard & Cutting-Decelle’s (2007) argument for understanding and estimating the value of interoperability to the business in terms of efficiency, differentiation and competitiveness. As the debate continues, and as alternatives to a standards-based approach to interoperability are being proposed, e.g., frameworks interoperability (Shen et al., 2010, p. 198), the argument for a broader definition of interoperability to include non-technical elements may be even more salient to resolving the problem.

As highlighted earlier, the paucity of literature addressing green design issues in technology implementations in the construction industry was a rather surprising finding of this review, in view of the current sustainability agenda in government and industry. This seems to be the case despite the current BIM drive in the industry. While the level of maturity of BIM may be a factor, the issue of organisational commitment to sustainable design was also indicated (see (Young Jr. et al., 2008, p. 20)). However, the concept of sustainable design is itself a “contested notion” (Nielsen et al., 2005). This makes the usefulness of tools context-dependent. Furthermore, this contestation may be an indication of the firm’s philosophical approach to the concept of sustainability, i.e., defined narrowly, as a means of achieving “organizational effectiveness” (Jennings & Zandbergen, 1995), or broadly, as a goal that encompasses systemic and cultural changes reflecting the realities of the organisation’s ecosystem. That more recent research (Young Jr. et al., 2009, p. 26) shows BIM having
limited impact on green building processes today is, perhaps, an indication of firms’ ambivalence about its green credentials, despite many predicting it could be a valuable tool in the coming years.

The preceding paragraphs have discussed some of major issues and challenges affecting the implementation of digital technologies in an integrated project delivery environment. These notwithstanding, some challenges to the implementation of digital technologies were evident in the review. The most salient among these include the material constraints and affordances (Leonardi & Barley, 2008) occasioned by the technology being implemented e.g., (Edum-Fotwe et al., 2004; Staub-French & Khanzode, 2007; Goedert & Meadati, 2008), the challenge of providing good leadership and what happens when it is missing (Aranda-Mena et al., 2009; Dossick & Neff, 2010b), and information-related risks (Fischer et al., 2003; Young Jr. et al., 2008; Aranda-Mena et al., 2009) and limitations (Staub-French & Khanzode, 2007). Others include problems of training and the scarcity of skilled professionals (Bibby et al., 2006; Staub-French & Khanzode, 2007; Post, 2008; Young Jr. et al., 2008), and the challenge of accurate measurement of value (Li et al., 2009; Young Jr. et al., 2009) of such implementations.

3.3 Conclusion

In this review, the evidence of actual implementations of integrated digital technologies in major building and infrastructure projects was investigated using a systematic methodology (Tranfield et al., 2003; Pittaway et al., 2004; Rousseau et al., 2008; Denyer & Tranfield, 2009). The evidence indicates that the integration of disciplines, stages and systems in design and construction activities is a key aim of major projects and an underlying theme of integrated approaches to project delivery. The application of digital technologies has not permeated all segments of the industry and, even in major projects, they are not always used in an integrated manner. Rather, they are often applied in one area (Hartmann et al., 2008), although at the same time, multiple technologies may be used in that one area. The perennial challenge of interoperability has been attributed to the heterogeneous applications and systems in use and the dynamism and adaptability necessary to operate in the industry. There have also been calls for a broader definition of interoperability to include non-technical systems, while a frameworks approach has been suggested as an alternative to traditional standards-based approaches.

Furthermore, the use of digital technologies is dearly more evident in the design and construction disciplines and stages of the asset lifecycle, than in operations and facilities management. The latter have traditionally used and to a large extent continue to use paper-based processes and tools such as drawings and spreadsheets (Ahamed, Neelamkavil, & Canas, 2010). The reasons for this are far from understood and must needs be, if the goal of the integrated approach, of incorporating members “well beyond the basic triad of owner, architect, and contractor” (AIA, 2007) is not to be undermined. However, the state of play described above suggests that there is still the problem of definition of what an integrated approach to project delivery entails, i.e., to what extent vis a vis whole lifecycle management and the enduring feature of fragmentation of the industry, as well as misconceptions or misapprehension about technologies such as BIM, especially among smaller firms. Hopefully, this review has succeeded in identifying some of the real challenges faced in this regard.
The review’s contribution, however, lies as much (or more) in what it did not find as in what it found. Despite almost two decades of implementation of digital technologies in one type of integrated project delivery practice or another, the real evidence uncovered can at best be described as parsimonious. For instance, much research effort is currently tilted towards developing new tools as evidenced by the large number of experimental and early development publications excluded from the review. On the other hand, there is much left to be understood about the real benefits and challenges of existing BIM (and related) solutions. Additional research effort would increase this understanding and with it, help the industry and policy makers make better informed decisions about the application of these technologies in the digital construction economy of the future.

The lack of evidence suggests some areas that could benefit from future research attention. These include: 1) More studies of BIM (or other integrated technologies) implementations in real construction projects; 2) Studies of how multiple technologies can be successfully integrated across the whole lifecycle; and 3) Studies of issues around the use of integrated digital technologies for green design and construction. Finally, the review is not without some limitations, e.g., the relatively small evidence base and the relaxation of aspects of the systematic methodology to allow for the expansion of the evidence. These may be addressed by revisiting the literature in the next few years, when some of the policy targets are due. This would not only provide a larger evidence base but also a more robust basis for comparison between policy objectives and industry realities.

3.3.1 Acknowledgements

The author wishes to especially acknowledge the Design Innovation Research Centre’s Director, Prof. Jennifer Whyte, for generally supporting this work, giving invaluable advice that helped in shaping the methodology, and taking the time to severally review and comment on many aspects of the review and this working paper. Colleagues at DIRC, Dr. Carmel Lindkvist and Dr. Wei Zhou also participated in the methodology meetings and offered helpful suggestions, while Suha Jaradat and Sonja Oliveira contributed by reviewing some of the papers. Prof. Martin Fischer of Stanford’s Centre for Integrated Facilities Engineering (CIFE) also gave useful advice and suggested some relevant material. Phil Jackson, Chair of the ICE-IS Panel and Steve Jolley, Global Business Development Director at Bentley Systems, offered constructive advice during a technology briefing that helped inform the review’s methodology. The author is sincerely grateful for the contribution of all the aforementioned but takes full responsibility for any errors that may be found. The research was funded by the Design Innovation Research Centre’s EPSRC award no. EP/H02204X/1.
References


Appendix A: Inclusion and exclusion criteria

### Inclusion Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Reason for inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Empirical quantitative and qualitative studies</td>
<td>To capture all types of empirical evidence available and improve the confidence in the review’s findings</td>
</tr>
<tr>
<td>2. Research from US/Europe/Middle East/Japan/Australia</td>
<td>Some of the world’s leading AEC firms in these countries/regions; more likely to have been studied; to ensure capture of internationally leading projects.</td>
</tr>
<tr>
<td>3. Working papers</td>
<td>Ensure coverage of the most current research</td>
</tr>
<tr>
<td>4. Industry literature</td>
<td>Capture good quality industry studies of relevant projects otherwise not studied through academic research</td>
</tr>
<tr>
<td>5. Theoretical papers</td>
<td>Provide working assumptions to be used in the SLR paper; strong theoretical bases for progressing DIRC research out in the field.</td>
</tr>
</tbody>
</table>

### Exclusion Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Reason for exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pre-2000</td>
<td>Focus on BIM and digital tools for innovation in construction fairly recent; terminology and technologies have changed</td>
</tr>
<tr>
<td>2. Research prototypes</td>
<td>Exclude early work/development</td>
</tr>
</tbody>
</table>
### Appendix B: Summary of the nature of the evidence

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Study type</th>
<th>Main/relevant finding(s)</th>
<th>Strength/(weakness)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aranda-Mena et al.</td>
<td>2009</td>
<td>Multiple case studies</td>
<td>BIM enhances technical, operational and business capabilities across the project life cycle.</td>
<td>Moderate. Propositions supported by case studies.</td>
</tr>
<tr>
<td>Babic et al.</td>
<td>2010</td>
<td>Experimental</td>
<td>BIM can be used as a link between an enterprise resource planning (ERP) information system and CAD tools. Reported benefits to project progress monitoring and material flow management.</td>
<td>Moderate. Demonstrated in a real project environment</td>
</tr>
<tr>
<td>Bellamy et al.</td>
<td>2005</td>
<td>Ethnography</td>
<td>Different communication skills are required for the successful use of digital technologies because the interaction processes between virtual and co-located teams are different.</td>
<td>Moderate. Used Bales’ (1951) Interaction Process Analysis (IPA) to develop a theoretical framework, which was then validated in a real project.</td>
</tr>
<tr>
<td>Bendixen &amp; Koch</td>
<td>2007</td>
<td>Ethnographic case study</td>
<td>Visualisation tools (mostly CAD drawings) can be used as negotiation and influencing tools in the briefing phase of design, even without the input of other engineering expertise.</td>
<td>Strong. Case study of 3 groups in one company, involving observation, document analysis, and 35 interviews.</td>
</tr>
<tr>
<td>Bibby &amp; Bouchlaghem</td>
<td>2006</td>
<td>Mixed methods</td>
<td>Co-ordination tools are important to effective design management. They delivered critical and supportive impact. However, many participants did not use an integrated management system (IMS) because it did not provide any additional information to a paper handbook and because of difficulties with access, format and navigation.</td>
<td>Moderate. Evaluation of design management training initiative. Methodology included a structured questionnaire, design management maturity assessment, semi-structured interviews and a case study.</td>
</tr>
<tr>
<td>Cerovsek</td>
<td>2010</td>
<td>Review</td>
<td>Critical review of features of over 150 tools and digital models in use in the industry from the point of view of standardisation. Recommendations for methodological and practical improvements to BIM tools and BIM schema standardisation. Argues that standard BIM schema can never be finished but must constantly evolve and improve. Standards play three important roles; inter-operability, trust, and comparability. Partial progress has been made in the former, but not at all in the latter two.</td>
<td>Strong. Comprehensive review.</td>
</tr>
<tr>
<td>Doloi</td>
<td>2010</td>
<td>Experimental</td>
<td>A simulation approach to managing design at an early stage of a project has benefits. These include the ability to quantify the impact of changes and the functionality to make those changes. It allows design professionals to analyse what-if scenarios and</td>
<td>Strong. The proposed approach was demonstrated in a real case study and the multi-criteria decision analysis (MCDA) added confidence to the findings.</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Year</td>
<td>Study Type</td>
<td>Findings</td>
<td>Strength</td>
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<tr>
<td>Dossick &amp; Neff</td>
<td>2010a</td>
<td>Ethnographic case studies</td>
<td>BIM is useful for technological aspects of collaboration, but is often at odds with the dialogic aspects needed for problem-solving.</td>
<td>Strong. Observations in multiple settings, validated by comparisons with themes in over 70 interviews.</td>
</tr>
<tr>
<td>Dossick &amp; Neff</td>
<td>2010b</td>
<td>Ethnographic case studies</td>
<td>While BIM improves collaboration among project members, it accentuates organisational division, hence less collaboration between firms.</td>
<td>Strong. Observations in two case studies over 12 months supported by comparisons with data from 65 interviews.</td>
</tr>
<tr>
<td>Edum-Fotwe et al.</td>
<td>2004</td>
<td>Case study</td>
<td>The use of a central standardisation database (CSD) approach helps reconcile the discrepancy between standardisation and innovation. It enables architects and design engineers exercise design freedom without undermining the need for consistency and alignment with industry developments.</td>
<td>Moderate. Single case study but with potential for wider applicability in the construction (or related) industries.</td>
</tr>
<tr>
<td>El-Tayeh &amp; Gil</td>
<td>2007</td>
<td>Experimental (includes case study)</td>
<td>Developed a new methodology for evaluating the usability of digital prototypes to support socialisation among virtual engineering design teams.</td>
<td>Moderate. Authors accept limitation in that despite exploring the early design phase of a real project, the reality may be different from the subsequent validation in a laboratory setting.</td>
</tr>
<tr>
<td>Ewenstein &amp; Whyte</td>
<td>2007</td>
<td>Ethnographic case study</td>
<td>Visual representations as “artefacts of knowing”, mediate knowledge both as symbolic representations and material entities for interaction.</td>
<td>Strong. Although the study investigated paper-based visualisation tools, it speaks to the visualisation characteristics of digital technologies as well.</td>
</tr>
<tr>
<td>Fischer</td>
<td>2003</td>
<td>Multiple (short) case studies</td>
<td>Virtual building tools can enable designers, builders, and owners to test any aspect of a project’s design, organization, and schedule before committing significant resources to the project.</td>
<td>Moderate. Despite the resonance of the short cases of major projects, the methods of data collection were not apparent.</td>
</tr>
<tr>
<td>Fischer et al.</td>
<td>2003</td>
<td>Multiple case studies</td>
<td>All owners and AEC service providers who have used 4D models to understand, analyse and communicate a design and construction schedule have reported benefits.</td>
<td>Strong. Includes a detailed case study of a major construction project and how 4D model was used for construction scheduling and constructability analysis and the technical challenges faced.</td>
</tr>
<tr>
<td>Fox &amp; Hietanen</td>
<td>2007</td>
<td>Field study</td>
<td>Despite some identifiable barriers (technological and organisational), the inter-organisational use of BIM can lead to informational, automational, and transformational effects across organisations.</td>
<td>Moderate. Field study of 20 organisations at the use stage of innovation diffusion. However, the data collection and analysis were not transparently shown.</td>
</tr>
<tr>
<td>Froese</td>
<td>2010</td>
<td>Theoretical/methodological</td>
<td>Proposal for a unified approach to construction project management based on a representational framework and</td>
<td>Moderate. Case for proposed approach is made via an incisive analysis of</td>
</tr>
</tbody>
</table>
general methodology. Argues that some type of ICT platform is a minimum practical requirement for this approach. This can provide integrated, computer-based collections of all known project information, including geometric (3D models) and non-geometric (e.g., cost and scheduling) information.

<table>
<thead>
<tr>
<th>Source</th>
<th>Year</th>
<th>Type</th>
<th>Description</th>
<th>Methodology</th>
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</thead>
<tbody>
<tr>
<td>Gal et al.</td>
<td>2008</td>
<td>Case study</td>
<td>Boundary objects (3D technologies) are intricately intertwined with organisational practices and organisational identities. Changes in the boundary objects usually bring about changes in the organisational practices and identities.</td>
<td>Strong. Robust theoretical framework and an in-depth case study of a major US general contractor in multiple projects.</td>
</tr>
<tr>
<td>Goedart &amp; Meadati</td>
<td>2008</td>
<td>Fieldwork and case study</td>
<td>BIM software was found useful in one project phase but not specifically suited to another phase until modifications to the software as well as procedures were made.</td>
<td>Strong. The research project ran in parallel with the real project but did not directly influence the project outcome. However, it showed the feasibility of extending BIM throughout the project life cycle. A method of data collection using robotic technology was also used.</td>
</tr>
<tr>
<td>Grilo &amp; Jardim-Goncalves</td>
<td>2010</td>
<td>Theoretical</td>
<td>Technical interoperability is not the problem for the construction industry in implementing BIM, but understanding and determining the value of such interoperability to the business.</td>
<td>Moderate. Detailed analysis of technical developments related to BIM in the industry. Evidence to support claims about firms’ views on the business value of interoperability is not clear.</td>
</tr>
<tr>
<td>Hartmann &amp; Fischer</td>
<td>2007</td>
<td>Case study</td>
<td>Product and process knowledge can be communicated more efficiently using 3D/4D models as knowledge visualisation tools during the constructability review. Improvement in collaboration among the project team was reported.</td>
<td>Moderate. Data was collected over a period of 1 year while one of the researchers was part of the project team. However, the method of data analysis is not clear.</td>
</tr>
<tr>
<td>Hartmann et al.</td>
<td>2008</td>
<td>Multiple case studies</td>
<td>Most projects have applied 3D/4D models for only one application area in one project phase, mainly in the pre-construction phases.</td>
<td>Strong. Aggregated results of 26 case studies in several countries qualitatively analysed, not to replicate findings but to offer a broader view.</td>
</tr>
<tr>
<td>Howard &amp; Bjork</td>
<td>2008</td>
<td>Survey (qualitative)</td>
<td>BIM solutions appear too complex for many and as such, may need to be applied in limited areas initially.</td>
<td>Moderate. Although study claims to be qualitative and expert opinions were collected, no robust method of analysis was evident.</td>
</tr>
<tr>
<td>Huang et al.</td>
<td>2009</td>
<td>Mixed methods</td>
<td>Visualisation and communication functions of software used in the CVP approach are the most useful. Collaboration between</td>
<td>Strong. Data collection and analysis methods were robust and transparently</td>
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<tr>
<td>Design Innovation Research Centre</td>
<td>Working Paper, Number 3</td>
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<tr>
<td><strong>Isikdag &amp; Underwood</strong> 2010</td>
<td>Theoretical/methodological</td>
<td>3D/4D CAD technology and Lean production methods can be combined, and the project team organised to take advantage of this combination to create maximum value and continuous flow of information during the design phase. Guidelines are also provided.</td>
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<tr>
<td><strong>Khanzode et al.</strong> 2005</td>
<td>Case study</td>
<td>3D/4D CAD technology and Lean production methods can be combined, and the project team organised to take advantage of this combination to create maximum value and continuous flow of information during the design phase. Guidelines are also provided.</td>
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<tr>
<td><strong>Koo &amp; Fischer</strong> 2000</td>
<td>Case study</td>
<td>4D models can be used as visualisation, analysis, and integration tools. They enable “even relatively inexperienced users to identify problems previously overlooked in the original schedule”. They are also a useful alternative to project scheduling tools like CPM networks and bar charts, in conveying a construction schedule.</td>
<td></td>
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<tr>
<td><strong>Kunz &amp; Fischer</strong> 2009</td>
<td>Theoretical/methodological</td>
<td>Companies making multi-disciplinary use of integrated 3D/4D models throughout the project life cycle - virtual design and construction (VDC), find that it consistently improves business performance. Observed limitations in practice reported.</td>
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<tr>
<td><strong>Li et al.</strong> 2009</td>
<td>Mixed methods</td>
<td>Virtual design and construction (VDC) can be better implemented in areas where benefits could be tangibly measured than in those where measurements are more difficult or not possible. VDC can alleviate many problems of contemporary Project Management although it (VDC) many challenges remain.</td>
<td></td>
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<tr>
<td><strong>Nakamura et al.</strong> 2006</td>
<td>Case study</td>
<td>3D CAD data can be used to confirm and correct the correspondence of planning between two companies from the early stages of the project using total process simulation. Partial process simulation can be used to make changes to on-going</td>
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<tr>
<td>Author</td>
<td>Year</td>
<td>Methodology</td>
<td>Findings</td>
<td>Quality of evidence</td>
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<tr>
<td>Robinson</td>
<td>2007</td>
<td>Case study</td>
<td>Structural steelwork detailing has made a remarkable shift from 2D drawing to 3D product modelling, enabled by a “finite number of software solutions”. Low. Methodology not very robust, but study is a rare example in the literature of using BIM for structural steel work. Author’s expertise also taken into account.</td>
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<tr>
<td>Schroepfer</td>
<td>2006</td>
<td>Case study</td>
<td>IT tools were found to be crucial to collaboration among global project teams. But team member soft requirements (e.g., communication skills and motivation and commitment) turned out to be at least as crucial as technical requirements. Moderate. Study was part of a research project that re-enacted a major infrastructure project, with 40 participants including researchers, students, and industrial collaborators. However, the data collection and analysis method was not clear; neither was how the study data compared with the actual project.</td>
<td></td>
</tr>
<tr>
<td>Shen et al.</td>
<td>2010</td>
<td>Review</td>
<td>An alternative to data interoperability approach is that of frameworks interoperability, which is more suitable for distributed and loosely coupled integration environments. Technologies for achieving frameworks interoperability include commercially available Web-based systems and the (intelligent) agent-based systems. There is little evidence of the latter in actual projects. Strong. Comprehensive review.</td>
<td></td>
</tr>
<tr>
<td>Staub-French &amp;</td>
<td>2007</td>
<td>Case study</td>
<td>Visualisation and communication capabilities of 3D tools were their most useful functionality. Each team member’s commitment to modelling their respective scope of work in 3D CAD using a design-build, concurrent engineering (CE) approach, before the start of design and construction, played a significant role in the success of the project. Bringing project team together early improves ability to capitalise on benefits of 3D tools. Strong. Research team members actively participated in, observed and documented the activities of the construction team for a major project. Methods used were, however, not clear.</td>
<td></td>
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<tr>
<td>Khanzode</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Staub-French &amp;</td>
<td>2007</td>
<td>Case studies</td>
<td>Reported benefits of implementing 3D/4D technologies include and provided guidelines for overcoming the technical, procedural and organisational challenges associated with implementing these technologies. Identified 10 steps essential to setting up a 3D design coordination process. Strong. The author’s roles on the two projects and those of other project participants were reported transparently. However, the data collection and analysis methods are not clear.</td>
<td></td>
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<tr>
<td>Khanzode</td>
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<tr>
<td>Suermann &amp; Issa</td>
<td>2007</td>
<td>Mixed methods</td>
<td>Implementing BIM improves all six industry key performance indicators (KPIs) of quality control, on-time completion, cost, simulation. Methodology not clear. Strong. Although the results are of the survey phase of the research, the</td>
<td></td>
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<tr>
<td>Authors</td>
<td>Year</td>
<td>Methodology</td>
<td>Findings</td>
<td>Strengths</td>
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</tr>
<tr>
<td>Taylor &amp; Bernstein</td>
<td>2009</td>
<td>Mixed methods</td>
<td>Identified four emergent BIM practice paradigms: visualisation, coordination, analysis, and supply chain integration. Inter-organisational practices evolve as BIM practices evolve. Understanding and developing inter-organisational work practices is essential to reaping the benefits of BIM, methodology for all phases was clearly described.</td>
<td>Strong. Robust methodology, described in detail. Examined 26 distinct cases of BIM use across several countries and disciplines. Link between data and findings clearly transparent in both the qualitative and quantitative analyses.</td>
</tr>
<tr>
<td>Whyte &amp; Lobo</td>
<td>2010</td>
<td>Case study</td>
<td>Digital objects provide mechanisms for accountability and control and for mutual and reciprocal knowledge sharing. Different types of objects are nested, forming a digital infrastructure for project delivery. Cross-organisational boundaries sometimes hinder mutual knowledge sharing.</td>
<td>Strong. Robust interpretive methodology: detailed case data from in-depth interviews, secondary sources and archival analysis of organisational database; rich descriptions to support findings.</td>
</tr>
<tr>
<td>Whyte et al.</td>
<td>2007</td>
<td>Ethnographic case studies</td>
<td>Visual representations (both digital and physical) may be used in a frozen (inflexible) or unfrozen (flexible) manner to achieve different purposes at different stages of design. This pattern of freezing and unfreezing plays an important role in design practice.</td>
<td>Strong. Rigorous methodology involving detailed data collection and analysis. The two contrasting research settings allow more confidence in the findings and their extensibility.</td>
</tr>
<tr>
<td>Yoo et al.</td>
<td>2006</td>
<td>Ethnographic case studies</td>
<td>An organisation's design (i.e., structure) is a consequence of its organisation designing (i.e., an ongoing process), not the other way round. Organisation designing is a function of the organisation's &quot;design gestalt&quot; which is &quot;an organisation's ability to approach its design problems creatively and individually, yet maintain unity across design outcomes&quot;. The case study organisation's design gestalt consists of an architectural vision, the tight coupling of multiple representation technologies, and a collaborative design network.</td>
<td>Strong. Rigorous methodology - multiple case studies within the same organisation and method triangulation (83 interviews, review of documents, and observation over a period of 3 years).</td>
</tr>
<tr>
<td>Young Jr. et al.</td>
<td>2007</td>
<td>Industry survey</td>
<td>Interoperability issues impact data sharing in the global construction industry. A majority of the industry lists software incompatibility as the major factor affecting the ability of project team members to share data across different systems. However, only about a quarter of project team members are concerned about efforts at improving interoperability through development of data standards. BIM is seen as a critical catalyst in efforts at addressing the problem of interoperability.</td>
<td>Strong. Survey augmented with several case studies. Clearly described market research methodology.</td>
</tr>
<tr>
<td>Authors</td>
<td>Year</td>
<td>Methodology</td>
<td>Summary</td>
<td>Methodological Quality</td>
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</tr>
<tr>
<td>Young Jr. et al.</td>
<td>2008</td>
<td>Industry survey</td>
<td>Projects using BIM are realise productivity gains, improved communication, and competitive advantage. A majority of users report not only productivity gains but improvements to internal project processes. However, users have also experienced obstacles and challenges to implementing BIM (e.g., software costs and training issues) and see the need to balance productivity gains with these challenges.</td>
<td>Strong. Survey augmented with several case studies. Clearly described market research methodology.</td>
</tr>
<tr>
<td>Young Jr. et al.</td>
<td>2009</td>
<td>Industry survey</td>
<td>BIM brings project teams together, whether the aim is exchange data seamlessly or to share ideas more effectively. Obstacles to team working are among the biggest challenges faced by users. As experience and skill with BIM advance, impact on productivity benefits significantly increases. However, direct impact on profitability remains relatively low.</td>
<td>Strong. Survey augmented with several case studies. Clearly described market research methodology.</td>
</tr>
</tbody>
</table>