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REVIEWING THE EVIDENCE: USE OF DIGITAL COLLABORATION TECHNOLOGIES IN MAJOR BUILDING AND INFRASTRUCTURE PROJECTS

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SUMMARY: *In today's digital economy, the construction industry is at the verge of a technological revolution. Myriad technologies are promising innovative solutions to 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. However, there is limited understanding of how these technologies are actually implemented to separate myth from reality. This paper reports on a study, the main aim of which is to enable a better understanding of how digital collaboration technologies are actually used in major construction projects and to what benefit. The objective is to unearth the research evidence through a rigorous process, and to identify, synthesize and interpret this evidence. Through an adaptation of the systematic review methodology, this paper explores the evidence, showing how digital collaboration technologies are being used in the delivery of major building and infrastructure projects. The review finds that these technologies have been severally theorised as boundary objects and digital infrastructure, and as tightly-coupled and clean technologies. The main trajectories that characterise their development and use include visualisation, coordination, automation, integration and transformation. The evidence suggests that integration of people, processes and systems is the underlying and predominant theme in a majority of projects. However, instead of a truly integrated approach, projects have often used digital technologies to achieve partial integration, with design and construction phases having more applications than operations and facilities management. It was also found that digital technology implementations addressing sustainability issues have received less attention, in spite of current government and industry focus on that agenda. The review indicates a diversity of approaches to achieving integration, which means that a clear and uniform approach has yet to be established. Nonetheless, Building Information Modelling (BIM) appears to be the emerging leading paradigm, although it also means different things to different people. The perennial challenge of interoperability still remains, prompting calls for a broader definition to include non-technical aspects. Other major challenges identified in the review include the technologies' material constraints and affordances, leadership, information-risks, training and the measurement of value. Finally, the review highlights areas that could benefit from further research attention. These include more focus on actual BIM implementations in major projects, the challenges of integrating multiple technologies across the whole project/asset lifecycle; and closer attention to their use for addressing sustainability issues.*

KEYWORDS: *digital technologies, collaboration, coordination, BIM, integration, major projects, practices.*

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1. INTRODUCTION

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 the construction industry on this and other challenges confronting it, to derive full value from, and exploit the growth potential in the "public procurement of construction and infrastructure projects" (BIS, 2011a, 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 et al., 2010). In the UK, government is concerned that the industry has not fully taken advantage of the "full potential offered by digital technology" (BIS, 2011a, p. 13). A study of the adoption of Building Information Modelling (BIM) related technologies in the Australian construction industry argues that lack of industry experience and inputs is hindering their advancement and adoption (Gu & London, 2010). In the Netherlands, where policy changes in the health sector favour life-cycle considerations and multi-disciplinary collaboration on hospital building projects, the ICT support , i.e., BIM implementation, was described as "suboptimal" (Sebastian, 2011, p. 186). This paper is a timely contribution to this ongoing discourse.

In recent 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. The role of these technologies 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), the processes by which they become embedded into knowledge-creating practices (Baxter & Berente, 2010), and their use by small and medium-sized construction firms (Acar et al., 2005). Henderson (1991, p. 449), highlighted 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". 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.

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, scholars have raised 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, 2010). The research landscape, therefore, is quite in need of a systematic review of the literature. This paper reports on such a study, the main aim of which is to enable a better understanding of how digital collaboration technologies are actually used and to what benefit. The objective is to unearth the evidence through a rigorous process, and to identify, synthesize and interpret this evidence. This involved conducting a review of the research literature using an adaptation of the systematic review methodology detailed below. The scope of the review covers the most recent research evidence (2000-2012) on the use of digital collaborative technologies and practices in major building and infrastructure projects.

2. METHODOLOGY

The methodology adopted for this review is based on the systematic methodology developed in evidence-based medicine (Mulrow, 1994; Mulrow et al., 1997), and adapted for the management field by Tranfield and colleagues (Tranfield et al., 2003; Pittaway et al., 2004; Rousseau et al., 2008; Denyer & Tranfield, 2009). Due to space limitations, only the key elements of the methodology are highlighted here. It was developed through a series of meetings and refinements by the author and three colleagues and one consultation meeting with two industry experts. These entailed discussing the focus of the review, identifying initial keywords, key journals and databases, and the inclusion and exclusion criteria for the literature. The latter are presented in the appendix.

Extensive searches were carried out over several weeks in August, September, and October 2010, using search strings as in the example in Figure 1, in various combinations, using other delimiters such as publication date and type. The searches covered the major academic databases including ISI Web of Knowledge, Science Direct, EBSCO, and ICONDA. Construction databases searched include ARCOM, Intute, BUBL, PLANEX, Urbadoc and the ICE Virtual Library.

Design (w) innovat(w) digital; 3D CAD; Integrated (w) software (w) solution*; Integrated (w) software; BIM; Building (w) information (w) model*; Practice* (w) digital; Organi?ation* OR organi?ing (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*

FIG 1: Keywords and search string

Further searches were conducted in April 2012. These were limited to ISI Web of Knowledge, Science Direct, and EBSCO, but used the same search criteria as the 2010 searches and limited to the period 2010-2012. Industry sources and an EndNote library of academic and industry literature used by colleagues for a previous project were also consulted. The latter provided a few relevant articles in addition to those recommended by two academic experts in the field. An EndNote library with a total of 400 materials from all sources emerged as at April 2012. Out of these, abstracts of 248 considered potentially relevant were read and those not deemed relevant were eventually excluded. This resulted in 206 articles (175 from the 2010 searches and 31 from the 2012 searches) deemed, according to degree, to be of high (A), medium (B), and low (C) relevance.

In line with Pittaway et al.'s (2004) precedent, the review mainly covers literature categorized as (A) i.e., most relevant. Perception of degree of relevance was the author's but this was largely concurred by two colleagues. Based on this perception, abstracts of the most relevant articles had been coded in the qualitative analysis software NVivo after the 2010 searches. This was to identify themes that would further focus and frame the review. However, additional literature, from the 2012 searches and back searches of articles suggested by the two discipline experts, were subsequently included. In total, 71 of the 206 articles (50 from the 2010 searches and 21 from the 2012 searches), form the core of this paper, to a greater or lesser degree and as appropriate to the discussion.

A majority of the articles included in this paper are qualitative case studies of large-scale construction projects. These investigated project practices in relation to the use of digital technologies, but often involved mixed-methods, i.e., interviews, ethnographic observations, surveys of design professionals and other experts involved in project activities. Due to the paucity of the research evidence, some of the inclusion and exclusion criteria were relaxed in the review process. For instance, although the criteria excluded experimental or developmental studies, five such studies (Bellamy et al., 2005; Bibby et al., 2006; El-Tayeh & Gil, 2007; Babic et al., 2010; Doloi, 2010) were considered relevant as they have demonstrated applicability in a real project environment. Similarly, three other theoretical studies (Fröese, 2010; Grilo & Jardim-Goncalves, 2010; Isikdag & Underwood, 2010) were included as they were based on relevant analyses of trends and contextual issues in the construction industry backed by previous research.

Furthermore, previous related efforts are included in this review. These include four literature reviews that reviewed systems integration and collaboration in the construction industry (Shen et al., 2010); important BIM-related issues in major projects, such as interoperability, integration, model-based communication, and collaboration (Cerovsek, 2011); the relationship between digital design practices and construction safety in particular (Zhou et al., 2012); and in general, the wider implications of digital construction, as exemplified by BIM (Watson, 2011). Three industry reports of BIM adoption and implementation, based on surveys and case studies by McGraw Hill Construction (Young Jr. et al., 2008; Young Jr. et al., 2009; Bernstein et al., 2010), were also consulted, plus a study of BIM adoption and diffusion by Gu & London (2010) .

3. REVIEW FINDINGS

The findings represent a thematic analysis of the main issues that emerged from coding of the abstracts in NVivo and the subsequent review of the articles. The coding of abstracts was aimed at aiding the author in identifying and making sense of the most important issues covered by the literature. This reduced the need to review every "article in its entirety", in line with Pittaway et al. (2004, p. 141). It also had the advantage of enabling the reviewer to group articles according to themes and make judgments about the quality of the evidence (Tranfield et al., 2003; Pittaway et al., 2004). However, the subsequent approach to reviewing the articles proper was interpretive, which means that it relied on the author's sensemaking of the salient issues from the evidence after reading and interpreting the relevant articles whose abstracts were grouped under each theme. A working paper version of the review's findings was internally reviewed by a more senior colleague in June 2010. In sections 3.1 to 3.3, the review's findings are presented along the three major themes thus: theoretical perspectives; integration and interoperability; and, implementation practices. Table 1 also provides a summary of the thematic analysis of reviewed papers, showing the total number of papers representing each theme, although several studies have explored more than one theme.

TABLE 1: Summary of thematic analysis of reviewed papers

Main theme	Sub-themes	Example variants	Number of papers
Theoretical perspectives Studies that have proffered key theoretical perspectives on digital technology use	-	Boundary objects Tight-coupling Clean technologies Power relations Paradigm trajectories VDC development BIM diffusion Views of design management	10
Integration and interoperability Papers focused on integration of people, processes and systems in digital technology use	Integration of some stages/disciplines	Early (design) phases Single application area of project phase Construction phase	14
	Integration with project/asset lifecycle considerations	Across project life cycle Asset lifecycle (operations and maintenance)	10
	Integration of teams and networks	Communicative aspects Socialization and coordination Processes of embedding new technologies Practice paradigms Virtual teams	18
	Integration of systems (interoperability)	Technical interoperability (standards) Non-technical interoperability (definition)	12
Implementation practices Technology implementation practices	Implementation approaches, scopes and benefits	Bottom-up v. top-down approaches Communitarian approaches Internal/external scope Technical, operational and business capabilities	14
	User perceptions and expectations	-	5
	Implementation problems and challenges	Technology limitations Information risks Leadership Training Measurement of value	15
	Implementation guidelines	-	5
	Green implementation practices	Early consideration of sustainability issues Achieving certification Use for green retrofits	6

3.1 Theoretical perspectives

Digital technologies used in major design and construction projects have been described as boundary objects (Gal et al., 2008; Whyte & Lobo, 2010), as tightly coupled (Yoo et al., 2006) and clean technologies (Dossick & Neff, 2011). Boundary objects, first described by Star & Griesemer (1989), then Knorr-Cetina (1999), refer to objects used for creating knowledge and understanding at the boundaries of different scientific, professional, organisational and social worlds. 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 (Star & Griesemer, 1989, p. 393). In a case study of a major US general contractor, Gal et al. (2008) 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. The changes and 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). Similar examples of power relations with the introduction of ICTs, between the contractor and subcontractors, and between the temporary project organisation and the permanent organisation, are reported in the literature (Jacobsson & Linderoth, 2010).

However, conceptualising digital technologies used in design and construction as boundary objects is not without criticism. Whyte & Lobo (2010) argued that it focuses more attention 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 is also 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, 2011, p. 85). Thus it is seen as not entirely consistent with “messy talk”, the “unplanned, unforeseen and unanticipated” (Dossick & Neff, 2011, p. 85) dialogue that is inherent in, and necessary for conversation and problem solving in formal collaboration processes. But 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, 2011).

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.

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 (Taylor & Bernstein, 2009), the three stages of virtual design and construction (VDC) development - visualisation, integration, and automation (Fischer, 2006), and the automational, informational, and transformational priorities to which BIM has been applied in diverse projects (Fox & Hietanen, 2007). These trajectories, in the most part, appear to evolve cumulatively, with visualisation being the initial or most immediate, and aspects of the other trajectories co-evolving to varying degrees, from one project to another and as firms’ experience with BIM and other digital technologies matures.

Studies of 20 organisations that are in “the use stage” of diffusing BIM innovation (Fox & Hietanen, 2007) and 26 specific cases of firms using BIM tools (Taylor & Bernstein, 2009) highlight the importance of understanding inter-organizational work practices to reap the benefits of BIM. 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, while Taylor & Bernstein (2009, p. 75) concluded that inter-organisational practices “evolve as BIM practice paradigms evolve”. Similarly, it can be argued that the three views of design management, namely the conversion, flow, and value views (Khanzode et al., 2005), are closely related to the trajectories. So visualisation, the creation of continuous information/work flow, and value generation through minimising waste, are inbuilt in 3D/4D CAD-enabled processes, e.g., coordination, constructability analyses, and scheduling as described by Khanzode et al. (2005).

However, 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). With a few exceptions, Heikkilä & Jaakkola's (2003) description of an automated 3D blade control system for a road grader being one, there is scant evidence in the literature of the kind of automation that enables completion of work, for instance, as in the automobile industry. In the latter, robots can process digital information and handle whole sections of assembly with little intervention from humans. In the former, according to Dossick & Neff (2011, p. 91), "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". Arguably, the labour-intensive nature of construction work may ultimately limit the extent of development of the automational trajectory. The next section explores the second theme of the review's findings.

3.2 Integration

Integration is an underlying, even if not always obvious, theme in the reviewed articles. Similar to Gu and London's (2010) typology of product, processes and people, integration can be broadly divided into two; 1) the integration of people and processes, and 2) the integration of systems (i.e., interoperability). The latter is necessary to achieve the former, which is usually treated in 3 main ways: a) integration of some stages and disciplines of the project; b) with lifecycle considerations; or c) with a focus on building teams and networks. Integration of people and processes is discussed in more detail below in 3.2.1 to 3.2.3, while integration of systems, i.e., interoperability, is treated in 3.2.4. However, as in the literature and the rest of this paper, a degree of overlap is inevitable in the discussions.

3.2.1 Integration of some stages/disciplines

The use of 3D technologies has traditionally been the domain of design disciplines, with collaborative use across disciplines being a fairly recent development (Baxter & Berente, 2010; Singh et al., 2011). For instance, Samuelson (2008) reported a reduction in the use of hand drawings among architects and technical consultants. It is also argued that BIM as a design tool was originally aimed primarily at architects (Young Jr. et al., 2009, p. 46) and that its adoption and use favour "architectural, design, and pre-construction processes" (Ireland, 2010, p. C12). One survey 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). Another study of BIM use in two life-cycle construction projects in Kuopio, Finland (Soares et al., 2012), found that it has been more generally adapted to design use, while traditional ways of collaborating with other disciplines seemed to persist, both within design disciplines, and between designers and builders. A plausible explanation for this is that, unlike the design disciplines, builders and contractors who are responsible for turning the former's ideas into physical reality, i.e., buildings, have less understanding of the embedded nature of different forms of CAD (Baxter & Berente, 2010, p. 138). Not surprisingly, integration in the early stage of the project has received significant attention in the literature – see (Bellamy et al., 2005; Khanzode et al., 2005; Yoo et al., 2006; El-Tayeh & Gil, 2007; Ewenstein & Whyte, 2007; Hartmann & Fischer, 2007; Hartmann et al., 2008).

Such studies have focused on integrating various aspects of the early design phase. On a major healthcare project, Khanzode et al. (2005) studied 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, to create maximum value and continuous flow of information. Hartmann & Fischer (2007) also studied the use of 3D/4D models to support the constructability review process by supporting the communication and generation of knowledge. Indeed, 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.

Nonetheless, other project phases and proximal disciplines are getting increasing coverage in the literature. These include mechanical, plumbing and electrical (MEP)(Dossick & Neff, 2010), prefabrication (Babic et al., 2010; Li et al., 2011a), structural steel and concrete (Robinson, 2007; Hu & Zhang, 2011), and the construction phase (Goedert & Meadati, 2008). Robinson (2007) argues that a plethora of software solutions (including BIM) have enabled a remarkable shift in structural steelwork detailing from 2D drawings to 3D product modelling, while a BIM- and 4D-based system for structural safety and conflict management was trialled in 3 major projects, including the 'bird's nest' stadium used in the 2008 Beijing Olympics (Hu & Zhang, 2011). Babic et al. (2010) examined how mass production prefabrication processes are integrated with construction site activities 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.

In another case study, a hotel project using prefabricated construction (Li et al., 2011a), showed that virtual prototyping (VP) technology combined with the IKEA production process can enhance design coordination. This provided a collaborative platform which brings the various construction disciplines and participants together, thereby enhancing prefabrication design, production, transportation and installation, reducing cost and time, and improving safety and efficiency. Cost and time savings were also made in several other projects that applied this method (Li et al., 2011a). On the other hand, Dossick & Neff (2010) examined the use of BIM technologies for MEP and fire life safety systems coordination. However, concern has also been raised about the negative and unintended consequences of digital technology on safety, for instance, the potential for "mindlessness" that such technology may engender (Zhou et al., 2012).

3.2.2 Integration with project/asset lifecycle considerations

Studies have also investigated the use of digital collaboration technologies with lifecycle considerations. Three industry reports (Young Jr. et al., 2008; Young Jr. et al., 2009; Bernstein et al., 2010) surveyed how BIM was being used across the whole project and asset lifecycle from design to site excavation and energy analysis. According to Young Jr. et al. (2009, p. 7), with the exception of engineers who, at 48% reported least benefit in terms of sufficient functionality and return on investment, participants across the project life cycle – architects (58%), contractors (71%), and owners (70%) - reported positive benefits of using BIM. They also suggested that increasing the technology offerings for engineers may improve their perception. In the academic literature on the other hand, lifecycle considerations often focus on the efficacy of digital models in helping overcome technical, procedural, and organisational challenges across the project life cycle (see (Staub-French & Fischer, 2007; Staub-French & Khanzode, 2007; Aranda-Mena et al., 2009; Kunz & Fischer, 2009)). Nonetheless, evidence of actual use of integrated digital technologies in the entire project life cycle or beyond that into asset lifecycle is sparse. Indeed, the latter is mostly discussed in terms of the potential.

Lifecycle considerations often start from the early design phase, which is quite logical, since this would reduce the potential of costly and time-wasting changes to the design if considered at a later stage. For instance, 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, with a view to enabling design professionals to analyse what-if scenarios and fine tune the design over the project lifecycle. Through several short case studies, Fischer (2003, p. 61) 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". Hartmann & Fischer (2007) showed how 3D/4D models support the communication and generation of design, construction sequencing, and scheduling knowledge. In another study, multi-disciplinary teams used 3D CAD models linked to existing software solutions for activities throughout the lifecycle of a biotechnology plant construction project, from design, to coordination, estimation, planning, scheduling and project management (Staub-French & Fischer, 2007).

A multiple case study focusing on the work of architectural and engineering consultants, contractors and steel fabricators found that BIM enhanced technical, operational and business capabilities across the project life cycle (Aranda-Mena et al., 2009). Examples of these capabilities include 1) the ability to exchange models with consultants (technical capability); 2) the ability to "design in a 3D environment throughout the entire design process" (operational capability); and, 3) the ability "to complete larger design projects with greater efficiency than present" (business capability), the latter example being of particular importance to smaller firms (Aranda-Mena et al., 2009, p. 432). Similarly, 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) found that visualisation and communication capabilities of the tools were their most useful functionality. However, even when the full array of BIM functionalities is not utilised, the use of 3D models for visualisation and clash detection was found to lead to significant improvements, as seen in two hospital building projects (Sebastian, 2011). Using 3D visualisations, “design decisions and their consequences can be made visual almost immediately” (Sebastian, 2011, p. 184). Indeed, it is argued that only visual models have the power to support collaboration “by a broad class of stakeholders” (Kunz & Fischer, 2009, p. 37). 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).

3.2.3 Integration of teams and networks

Integration in the literature also broadly focuses on how teams and organisational networks interact and are supported by digital tools. It focuses on the interactive, communicative and inter-organisational aspects of project work (Bellamy et al., 2005; Fox & Hietanen, 2007; Hartmann & Fischer, 2007), the process of embedding new IT artefacts (Baxter & Berente, 2010), practice paradigms in project networks (Taylor & Bernstein, 2009), and socialization and coordination among virtual teams from diverse backgrounds (Schroepfer, 2006; El-Tayeh & Gil, 2007). Baxter & Berente (2010) identified four patterns in the process of embedding 3D CAD across three firms (a contractor and two subcontractors) involved in a highly innovative building project. These are: 1) motivation to embed 3D CAD in practice; 2) anchoring in the familiar; 3) experimenting with specific uses of 3D CAD in practice; and 4) confidence in using 3D CAD (Baxter & Berente, 2010, p. 141). These themes generally reflect ideas about how new IT artefacts are introduced, in relation to existing artefacts and practices, shaped through experimentation and actors’ frames of reference (Jacobsson & Linderoth, 2010), and integrated into existing processes (Whyte & Lobo, 2010), despite inevitable tensions between the old and the new (Baxter & Berente, 2010).

Studies of the use of digital tools from an organisational, rather than a purely technological perspective, help highlight their tight-coupling (Yoo et al., 2006; Ewenstein & Whyte, 2007) with exisiting tools and other organisational processes. In a study of the Fulton Street Transit Centre (FSTC) project in New York City, for instance, Hartmann & Fischer (2007) were not only interested in the project’s use of 3D/4D models, but also focused on how the project management team uses them to communicate project-generated knowledge to other participants or stakeholders that are non-engineers or non-project managers to support the constructability review process. In another project, effective collaboration 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).

The importance of integrating features of computer supported cooperative work (CSCW) with BIM to support socialisation among virtual project teams (El-Tayeh & Gil, 2007) has also been emphasised. Singh et al. argue that, BIM-server technologies “should not be limited to functional and operational requirements only” (Singh et al., 2011, p. 143), because AEC projects transcend disciplinary and organizational boundaries. The authors point to factors such as “lack of history and experience, conflicting goals, and varied roles and responsibilities” as inhibiting adoption of such technologies (Singh et al., 2011, p. 143). For instance, in El-Tayeh & Gil’s (2007) study, an extranet was not found to support socialisation across organisational boundaries due to limitations posed by professional liability issues. However, it has been suggested that as the legal framework for BIM develops such concerns seem to be fading (Young Jr. et al., 2009, p. 5). Furthermore, El-Tayeh & Gil (2007, p. 465) argue that other global developments impacting the industry are likely to result in the increased “use of digital media to support problem-solving across virtual AEC project teams”. These include 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 (El-Tayeh & Gil, 2007). BIM is also seen as helping to mitigate some key challenges of remote construction projects, e.g., “establishing shared understanding between the stakeholders located at discrete locations but involved in the same remote construction project” (Arayici et al., 2012).

Research on communication among both co-located and virtual teams, particularly in international projects, suggests changes in the nature of the interaction process between design professionals (Bellamy et al., 2005; Schroepfer, 2006). For instance, a virtual team interacting through an electronic white board asked proportionately more questions (and interacted differently, using the “Asks Orientation) than the co-located team, which used a more spontaneous “Gives Suggestion” interaction (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). Although such changes appear subtle, they may yet be significant, as more projects move from traditional co-located to virtual working environments.

In virtual environments, where 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 effective technology use. 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 and the types of media they use. These at different moments, may be “unfrozen” or “refrozen”, thereby either “opening up areas of design for negotiation by particular parties or closing down debate” respectively (Whyte et al., 2007, p. 26). Hence, it can be argued that AEC professionals will be increasingly required to be familiar with the different environments in which they have to work in and be equipped with the necessary skills they need.

3.2.4 Interoperability (integration of systems):

In the literature, interoperability has been discussed from a variety of technical and non-technical perspectives, but mostly the former. From a technical perspective, interoperability is described simply as “the ability to manage and communicate electronic product and project data among collaborating firms” (Young Jr. et al., 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 et al., 2007, p. 2). However, interoperability is still a problem in the AEC industry (Grilo & Jardim-Goncalves, 2010; Shen et al., 2010), despite many proposals to represent standardised data models and services, from the project life cycle to operations and maintenance. This is attributed to the many heterogeneous applications and systems in use and the dynamism and adaptability essential to operating in the industry (Shen et al., 2010). Bakis, Aouad, & Kagioglou (2007) argue that it is a result of the impossibility of developing a single building model that caters for all areas of construction. Therefore, different standards for interoperability target different segments of the AEC industry, with no common methodology for managing information exchange.

To ensure seamless information exchange between otherwise incompatible entities, several approaches may be adopted. A standards-based approach to achieving technical (or systems) interoperability is the main approach, although usually in combination with others such as the “semantic interoperability” and “software engineering” approaches (Pouchard & Cutting-Decelle, 2007, p. 121). The Industry Foundation Class (IFC) standard (IFC 2x3) is applicable to several construction disciplines (Bakis et al., 2007, p. 587), although 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).

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, at 41%, is among the factors with the greatest influence 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 (2011) critically reviewed the features of over 150 tools and digital models in use in the industry, and analysed the development, implementation, and use of the BIM schema from the standpoint of standardisation, arguing that assumptions used for such schema need to be revisited. He concluded that a BIM schema will never be complete, if it is to be able to support evolving technologies and practices, and should, therefore, be a living system (Cerovsek, 2011, p. 241).

Other discussions of interoperability may be described as focusing on interfaces or linkages. For instance, in a review of systems integration and collaboration in the AEC/FM industry, Shen et al. (2010) refer to such interfaces and linkages as frameworks interoperability. They argue that frameworks interoperability is more suitable for distributed and loosely coupled integration environments, which arguably, many major construction projects are. 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. Technologies for achieving frameworks interoperability include commercially available Web-based systems which are being used in the industry, and the (intelligent) agent-based systems which they can be implemented as. As yet, however, there is little evidence of the latter's implementation in actual projects (Shen et al., 2010).

Attempts at resolving interoperability challenges include the use of distributed object technologies. These are applications which have become more widely used for systems integration 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). However, in developing a distributed product data sharing design environment (Bakis et al., 2007, p. 590), it is argued that the Extensible Markup Language (XML) and its Web Services related technologies can be used as an alternative to distributed object-based technologies. Little evidence of such use in actual projects was previously available (Bakis et al., 2007), although it appears this will not be for much longer. For instance, a project was reported that used the IFC standard to implement BIM as a link between an ERP information system and construction object related information, mainly handled by CAD tools (Babic et al., 2010). Similarly, Grilo & Jardim-Goncalves (2011) point out that e-procurement and BIM have been linked through a service-oriented architecture for BIM (SOA4BIM), developed through an R&D project which has been successfully implemented and validated in the design phase of real projects. However, this was not without some unexpected challenges. For instance, corporate databases were found unsuitable for cost estimating and activity planning for "building elements" (Grilo & Jardim-Goncalves, 2011, p. 113), while BIM-based costing processes are fraught with difficulties due to existing estimation applications not being suited to BIM formats.

Finally, there are perspectives of interoperability which can be described as non-technical interoperability. These include human, inter-community and legal interoperability (Pouchard & Cutting-Decelle, 2007) and the cultural (Young Jr. et al., 2007) and business level (Grilo & Jardim-Goncalves, 2010) perspectives. Interoperability is also described as "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). BIM user perspectives on the developing elements of a BIM infrastructure, including the development of standards, have also been investigated (Young Jr. et al., 2008). 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. On the other hand, a strong argument was made for understanding and estimating the value of interoperability to the business in terms of efficiency, differentiation and competitiveness (Grilo & Jardim-Goncalves, 2010). As argued by Grilo & Jardim-Goncalves (2010), technical interoperability is not the problem for AEC in implementing BIM, as it has been shown to be feasible. Rather, the challenge is to understand and determine the value of such interoperability to the business, in essence making a case for a broader definition of interoperability.

3.3 Implementation practices:

Sections 3.1 and 3.2 explored two of the three main themes categorised in the reviewed literature on digital technology use in major projects. This section explores the third; implementation practices. Specifically, how the technologies (mainly BIM) have been actually implemented and their main benefits; major problems and challenges faced and how they were addressed; user perceptions and expectations; implementation guidelines suggested, and the green practices enabled.

3.3.1 Implementation approaches, scopes and benefits

From sections 3.1 and 3.2, it can be discerned that the integration of disciplines, stages, networks and/or technical systems is a common goal of digital technology implementations in major projects. However, there is a diversity of implementation benefits, scopes and approaches, from one project to another and even within projects. A few of these are discussed here. Starting with the approaches, Arayici et al. (2011), based on a recent implementation case study, had argued that a bottom-up, rather than a top-down approach leads to a more successful implementation of BIM. On the other hand, Bendixen & Koch (2007) had previously concluded that communitarian management approaches (Knorr Cetina, 1999) should be chosen to promote innovative briefing and design. In a more recent study of a major hospital building project, for instance, one client dedicated a relatively long preparation phase involving the architect, structural engineer and MEP consultant before commencement of design (Sebastian, 2011). This was aimed at creating a common vision of the optimal way of implementing BIM and the result was a document defining "the common ambition for the project and the collaborative working processes" (Sebastian, 2011, p. 183). Hartmann et al. (2012), on the other hand, provided evidence of the efficacy of a technology-pull strategy in actual BIM implementations, in contrast to the technology-push strategy, which often requires radical changes to work processes. According to the authors, the technology-pull strategy makes it possible to align tools to existing team processes, with attendant benefits such as reducing resistance to change and the risk of replacing existing processes that work well.

The scope of digital technology implementations reported varies considerably from project to project. In one major project, it was argued that rapid iterations using 3D and 4D models in the early (conceptual) design phase enabled efficient decision making (Khanzode et al., 2005, p. 146). In another, only the main building elements were included in the model to simplify the introduction of BIM, while other supporting material and elements were linked via external references and generally handled by an ERP system (Babic et al., 2010, p. 543). While the latter helped in integrating the two systems, BIM in this study was mainly used in a limited (internal) environment. In the Japanese nuclear power industry, planning and coordination of building construction and machinery installation had traditionally been made separately (Nakamura et al., 2006). However, in the construction of the turbine building of one nuclear power station, a 3D CAD system was used as a collaborative tool to bring the two together, by enabling the exchange of 3D CAD information between the building constructor and plant manufacturer (Nakamura et al., 2006). Using computer graphic animation and other commercial software, the 3D CAD system enabled total construction process simulation at the early stage of the project and partial process simulation for ongoing work adjustments (Nakamura et al., 2006).

BIM has been described as comprising "ICT frameworks and tools that can support integrated collaboration based on life-cycle design approach" (Sebastian, 2011, p. 180). On two major hospital building projects (Sebastian, 2011), multi-disciplinary design and engineering teams were required to collaborate using this approach. However, the difficulty was ensuring that other actors in the construction supply chain who were procured through traditional methods engaged in "integrated collaboration to generate sustainable design solutions that meet the life-cycle performance expectations" (Sebastian, 2011, p. 184). The implementation of BIM with more wide-ranging benefits was reported in multiple-case studies 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 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 tangible benefits of digital technology implementations were reported in studies conducted by researchers at Stanford University (Koo & Fischer, 2000; Fischer & Haymaker, 2001; Fischer et al., 2003; Khanzode et al., 2005; Staub-French & Fischer, 2007; Staub-French & Khanzode, 2007). At least 12 specific benefits were reported in a study of the activities of the construction project team for a biotechnology plant. These include fewer errors and less rework, fewer requests for information and change orders, better documentation and reproducibility of processes, improved communication of the schedule intent, and on-time and under-budget completion (Staub-French & Fischer, 2007, pp. 201-202). 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. Fischer & Haymaker (2001) and Fischer et al. (2003) also reported the benefits of applying 3D and 4D models for various stages and stakeholders in the project and asset lifecycle. 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).

Furthermore, while clients have generally used models to verify constructability prior to contract award, general contractors applied 4D models in more varied ways. For instance, in addition to communicating scope and schedule information to subcontractors and other parties, they were also beneficial 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. Finally, Koo & Fischer (2000) investigated the effectiveness of 4D models in conveying a construction schedule and found that the models are a useful alternative to project scheduling tools like CPM networks and bar charts. That there is less evidence of how these models are subsequently used, and their benefits, in asset operations and maintenance, indicates a general problem of reuse of project information highlighted recently by Li, Lu, & Huang (2009, p. 369).

3.3.2 User perceptions and expectations of BIM

Some studies have surveyed industry participants on the perceived benefits or value of BIM in major construction projects (Young Jr. et al., 2008; Suermann & Issa, 2009; Young Jr. et al., 2009; Ireland, 2010; Singh et al., 2011). Although architects are perceived to experience the most value (Young Jr. et al., 2009; Ireland, 2010), 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). 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). Tracking return on investment (ROI) remains a tricky proposition (Young Jr. et al., 2009); more will be said about the problems and challenges of measurement later in the paper. Suffice it to mention that Suermann & Issa (2009) indicate that users perceive BIM implementation as improving all six industry key performance indicators (KPIs) of quality control, on-time completion, cost, safety, dollar/unit, and units/man-hour to varying degrees.

User perspectives were also sought on the developing elements of a BIM infrastructure such as standards, content, software, training and certification, and on the use of BIM on green projects (Young Jr. et al., 2008). Young Jr. et al. (2009) indicate 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. However, some findings are divergent, which 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).

3.3.3 Implementation problems and challenges

In the literature, problems and challenges of integrated digital technology implementations that are often reported include cost, increased time/effort in creating 3D models, resource requirements, and coordination problems. For instance, in a landmark study of two major projects that implemented emerging 3D and 4D technologies, Staub-French & Khanzode (2007) reported limitations such as 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. However, only the most salient are highlighted here due to space constraints. Challenges discerned as particularly salient from this review include the constraints occasioned by the technology being implemented, information-related risks, organisational issues (specifically relating to leadership and training), and problems of accurate measurement of value. These are elaborated below.

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 and to submit completed designs and details of processes for each project for review by the centre. This was to ensure conformity to standards and guidelines, and 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 too (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).

Information risks: Information-related risks and problems have been reported in several studies as hindering, potentially or actually, the implementation of BIM (Fischer et al., 2003; Staub-French & Khanzode, 2007; Young Jr. et al., 2008; Aranda-Mena et al., 2009). In a study of the use of 3D and 4D models on a major project, Fischer et al. (2003) had reported information-related problems. 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. However, as found in a study of two major construction projects, updating the 4D model daily was quite a challenge. Yet it was a crucial task in representing "the as-built condition" and activities to be carried out during the week (Staub-French & Khanzode, 2007, p. 404). It is evident that the resolution (sometimes the immediate consequence) of these problems was often the additional time and resources needed to model the required information. Nevertheless, 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". While it is not clear whether these problems aggravated, or heightened concern over, information risks among the various project participants, it can be argued, nevertheless, that they have the potential. As such, they need to be given due consideration.

In other studies, concerns over such information risks were raised. Through five in-depth case studies of small, medium and large architectural and engineering practices, Aranda-Mena (2009) identified inhibitors towards the uptake of BIM. The main focus of analysis was the use of BIM authoring tools. Identified risks include those associated with ownership of information, intellectual property, 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 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).

Leadership: This was found to be a challenge in some projects (Aranda-Mena et al., 2009; Dossick & Neff, 2010). 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" (Dossick & Neff, 2010, 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" (Dossick & Neff, 2010, p. 466). Similarly, the problem of interoperability has often been resolved by simply adopting the same technology throughout the project. This requires leadership, which as Li et al. (2009, p. 370) found in several case studies, is often provided by the client's adoption of a software package and contractors having to do the same to maintain compatibility. However, Frank Gehry's example in Yoo et al. (2006), suggests that who provides this leadership, which, in this case, was the architect, may ultimately depend on the existing power relations.

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 (Aranda-Mena et al., 2009) and existing personnel often have to be trained to use a particular technology (Li et al., 2011a). 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 skilled participants are always trying to keep up with the more skilled players in the project. 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).

One suggested solution "to quicken the BIM learning curve 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). On the other hand, 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.

Measurement: A problem frequently faced in digital technology implementations is that of measurement of value or benefit, e.g., of ROI and actual cost savings. This was described as "tricky" in a report of six in-depth case studies that showed how BIM is solving real problems in actual projects (Young Jr. et al., 2009, p.8). In view of the variability and uniqueness of projects, however, obtaining data for making comparisons is difficult. Even where the data are obtained, wide variations are reported, as in Azhar (2011), where data from 10 projects were acquired from a mid-sized construction company to carry out ROI analyses. However, this was attributed to the use of real construction phase figures in some projects, and planning or value analysis phase figures in others (Azhar, 2011, p. 249). Similarly, Li et al. (2009) 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).

About half of projects surveyed by Young Jr. et al. (2009) tracked ROI as part of internal BIM implementation processes. 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). Rather than measure BIM's benefit as a whole, however, it has recently been suggested in a major project case study (Lee et al., 2012), that focusing on small and specific benefits (e.g., error detection), is a much simpler approach to measuring ROI. Similarly, using quantifiable data from three case studies, Barlish & Sullivan (2012) have provided a framework for measurement of specific benefits, i.e., return (e.g., change orders, requests for information (RFIs), and schedule) and investment (design costs and contractor costs) metrics.

3.3.4 Implementation guidelines

Studies have also offered practical implementation guidelines. These have potential implications on project practices and can be crucial to project outcomes; 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). Other guidelines 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 their case study of two projects, 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 associated costs. However, in other 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).

3.3.5 Green project implementations

The AEC industry is now paying particular attention to how the buildings of the future are designed, constructed and operated (Bernstein, 2007, p. 26). It has been argued that "the growth of green building as an accepted, widespread practice is helping to accelerate BIM adoption" mainly because "of the way BIM facilitates green design, construction and sustainable outcomes" (Bernstein et al., 2010, p. 1). A review of the literature and survey of construction professionals (Pitt et al., 2009) found that although the industry is taking some account of sustainability issues, more needs to be done. A more recent study 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., 2011b, p. 25). Based on a survey and case studies, BIM tools were described as presenting "significant opportunities" (Young Jr. et al., 2008, p. 5) in green design and construction practices. 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). It was 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. This was achieved by using BIM alongside performance analysis software. The latter "exchanged nearly all data seamlessly with the BIM", which was found to be a "good tool for real time and efficient dialogue" (Young Jr. et al., 2008, p. 20),. This resulted in improved outcomes, including 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). It also led them closer to the clearly defined target of LEED certification.

In another study (Bernstein et al., 2010), BIM was also perceived to be especially useful for green retrofit projects. 27% of "Green BIM practitioners" saw it "as highly applicable for use in green retrofits", while 49% saw it as "of medium applicability" (Bernstein et al., 2010, p. 4). Mah et al. (2011) showed how BIM can be implemented in sustainable construction practice. The study, conducted in a real housing project, 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).

Notwithstanding the aforementioned examples, primary focus on green design issues appears to be under-represented in studies of actual BIM use in construction projects. Studies that primarily 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". Nonetheless, benefits and potential synergies of integrating lean principles and 3D/4D CAD (Khanzode et al., 2005) or BIM (Sacks et al., 2010) from actual project implementations have been suggested, while a link has been made between lean construction principles and green practices (Lapinski et al., 2006).

The paucity of research evidence may also not be unconnected with the level of maturity of BIM in the industry, as "industry players agree that they are just beginning to tap the full potential of BIM to achieve their green objectives" (Bernstein et al., 2010, p. 4). 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 in this section, 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).

4. DISCUSSION

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, uniform approach has been established, nor is it necessarily feasible or desirable. 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 collaboration 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 aforementioned reason, it may also not be unconnected with project procurement arrangements, as the facilities management team is not 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 section 3.1, evidence suggests 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. From the foregoing review, it appears that this problem primarily 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). Yet again, 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). 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, 2011). 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 in section 3.3.5, 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 shows BIM currently having limited impact on green building processes (Young Jr. et al., 2009, p. 26) and limited market penetration (Bernstein et al., 2010, p. 4) is, perhaps, an indication of firms' ambivalence about its green credentials, despite many predicting it could be a valuable tool in the coming years.

5. CONCLUSION

This paper makes an original contribution to the literature by reviewing the evidence of actual implementations of digital collaboration technologies in major building and infrastructure projects. This was conducted using an adaptation of the systematic review methodology. 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. However, the application of these digital technologies has not permeated all segments of the industry and, crucially 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) or a few areas, although multiple technologies may be used at the same time even in one area. From this review, it can be argued that the use of integrated digital technologies is clearly 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 et al., 2010). The reasons for this need to be understood and addressed if the goal of the integrated approach, of incorporating members "well beyond the basic triad of owner, architect, and contractor" (AIA, 2007) is to be achieved.

This state of play suggests that there is still a problem of definition: in relation to what an integrated approach to project delivery is and what it entails, and in relation to interoperability. For instance, 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. However, calls have also been made for a broader definition of interoperability to include its non-technical elements, while a frameworks approach has been suggested as an alternative to traditional standards-based approaches to interoperability. The problem of definition also indicates the need to understand to what extent an integrated approach to project delivery can be achieved, for instance in relation to whole lifecycle management, the enduring feature of fragmentation of the industry, and misconceptions or misapprehension about technologies such as BIM, especially among smaller firms.

This paper has highlighted some of the major issues and challenges affecting the use of digital technologies in an integrated project delivery environment as evident from the review. Among the most salient, in the author's opinion, are 1) the material constraints and affordances occasioned by the technology being implemented, 2) the challenge of providing good leadership and what happens when it is missing, 3) information-related risks and/or limitations, 4) problems of training and the scarcity of skilled professionals, and 5) the challenge of accurate measurement of value. It is hoped that, by identifying these issues and challenges, this review has contributed to improving our understanding and encouraging further contributions from studies of real project environments.

However, the review's contribution also lies as much in what it did not find as in what it found. Despite almost two decades of implementation of digital collaboration technologies in one type of integrated project delivery practice or another, the real evidence uncovered can at best be described as parsimonious. Some industry surveys clearly suggest that BIM is enabling significant changes to the work practices of AEC (especially design) professionals, although there are, at times, divergent accounts as to how in the literature. Similarly, according to Hartmann, Gao, & Fischer (2010, p. 932), "most previous research used practical illustrations only to provide evidence for the technical feasibility of developing 3D/4D model prototypes". The large number of experimental and early development publications excluded from this review supports this view, and that much research effort is currently tilted towards developing new tools.

Consequently, there is much left to be understood about the real benefits and challenges of existing BIM (and related) solutions. For instance, whether BIM is a solution to practitioners' problems of interoperability, or whether it can be useful for spatial analysis compared with existing geographic information systems (GIS) tools, are still open questions (Bansal, 2010). Additional research effort on actual digital technology implementations in real projects 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. Specific areas that could benefit from future research attention include: 1) More studies of BIM implementations (and of other collaborative technologies) in real construction projects; 2) Studies of how multiple technologies can be successfully integrated across the project and asset lifecycle; and 3) Studies of issues around the use of integrated digital technologies for green design and construction.

Finally, I would like to offer some personal reflections on applying the systematic review methodology in this context. The approach presented challenges in unearthing the evidence for a topic with fuzzy or multiple borders and a diversity of perspectives that are still emerging. The relatively small evidence base unearthed meant that aspects of the methodology had to be adapted. For instance, simple searching of specific journals sometimes yielded more relevant or stronger articles than constructing complex searches on databases. A systematic review also takes a lot of time and effort and has better chance of a successful outcome if undertaken by a team, rather than an individual. Therefore, it needs the understanding and commitment of all team members throughout all stages of the review.

Regardless of the challenges, however, I believe that the process and resulting paper contribute to our understanding of how digital collaboration technologies are actually used in major building and infrastructure projects. Also, the review's limitations may further be addressed by revisiting the literature in the next few years as some policy targets start to draw near, e.g., the UK Department for Business Innovation and Skills (BIS) construction and BIM strategies (BIS, 2011a, 2011b). This would not only provide a larger evidence base but also a more robust basis for comparison between policy objectives and industry realities.

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APPENDIX - INCLUSION AND EXCLUSION CRITERIA

Inclusion Criteria

	Criteria	Reason for inclusion
1.	Empirical quantitative and qualitative studies	To capture all types of relevant empirical evidence available.
2.	Research from US/Europe/Middle East/Japan/Australia	To capture studies of internationally leading projects. The world's leading AEC firms operate, and their projects are more likely to have been studied, in these countries/regions.
3.	Working papers	To ensure coverage of the most current research.
4.	Industry literature	To capture good quality industry studies of relevant projects otherwise not studied through academic research.
5.	Theoretical papers	To provide working assumptions to be used in the paper and strong theoretical bases for progressing research in the area in future.

Exclusion Criteria

	Criteria	Reason for exclusion
1.	Pre-2000 studies	Scope boundary agreed with colleagues and industry experts as terminologies and technologies have changed in recent years, especially with the current industry focus on BIM and related digital tools in construction.
2.	Research experiments	To exclude early work/development (e.g., experiments and prototypes) as these would not have been fully implemented in a real project environment.