Loosely coupled systems of innovation: Aligning BIM adoption with implementation in Dutch construction

Papadonikolaki Eleni[1]

Abstract

As an innovation, Building Information Modelling (BIM) plays a key role in the digital transformation of construction industry. Whereas innovations affect and are affected by organizational behavior, they are better observed at a project level, as they are shaped by a network of various project actors. This study connects intra- (micro-) and inter-organizational (meso-) levels of BIM implementation. To explore the relation between BIM adoption drivers and BIM implementation in projects, three case studies are analyzed qualitatively through the theoretical lens of loosely coupled systems. The findings showed that although individual firms had strong external or internal BIM motivations and visions to adopt BIM innovation, the project networks rarely coordinated to support BIM implementation. Consequently, the project networks that were motivated by '*internal*' BIM adoption drivers (e.g. quality assurance), implemented BIM collaboratively and flexibly. Contrariwise, networks of firms that adopted BIM simply to comply with '*external*' demand (e.g. macroscopic market pressures or client demand), were rigid and competitive during BIM implementation and hindered knowledge transfer and innovation change management. Drawing upon the empirical data, other factors affecting BIM implementation and in need for further inter-organizational alignment were corporate compatibility, inter-firm knowledge mobility, and inter-firm power dynamics. The implication is the need for further alignment of visions about BIM innovation decision-making across firms to support effective BIM implementation in projects.

Keywords

Building Information Modeling (BIM), BIM adoption, BIM implementation, innovation, loosely coupled, project networks.

---

[1] Ph.D., Lecturer (Assistant Professor) in Builiding Information Modelling and Management, Bartlett School of Construction and Project Management, University College London, United Kingdom, phone: +44 20 3108 3219, email e.papadonikolaki@ucl.ac.uk

Introduction

Building Information Modeling (BIM) is a technological innovation that has the last decade gained traction in Architecture, Engineering, and Construction (AEC) industry as a construction innovation (Elmualim and Gilder 2014). Innovation entails new artefacts or processes in a field (Abernathy and Clark 1985). Overall, BIM domain entails a set of Information Technology (IT) tools for generating, managing, and sharing building information among project actors, involving more digital functionalities than three-dimensional modeling. Becerik-Gerber and Kensek (2009) studied trends of BIM in construction industry from a 'Building Information Management' perspective. Apart from technology, BIM is an innovation, as it brings new workflows for innovative project delivery and deeply transforms the intra- and inter-organizational settings.

However, not all firms and project networks are able to automatically work harmoniously with these new workflows and processes that accompany BIM innovation. After all, the network of AEC is fragmented into various firms that collaborate or compete across the market and it has been described as a 'loosely coupled system' (Dubois and Gadde 2002). Due to heterogeneity and fragmentation, innovation becomes misaligned among construction networks (Taylor and Levitt 2007). Similarly, as an innovation BIM tends to be misaligned among firms that adopt it. According to Taylor and Levitt (2007), construction systems with strong relational stability and permeable boundaries perform better with misaligned innovation – and probably with BIM innovation. To this end, a network view of BIM innovation offers a contextual understanding of BIM innovation and there is additional room to understand how BIM adoption drivers influence its implementation in project networks.

Any firm's decision-making on adopting BIM is the resultant of institutional forces, internal drivers, and external pressures (Kassem et al. 2015). The use of BIM has been mandated for governmental buildings from policy-makers in the United States of America (USA) and various

European countries, such as the United Kingdom (UK) and some Nordic countries. Such initiatives include quasi-contractual BIM documents among multi-disciplinary project actors, such as the pre-contract 'BIM Execution Plan' (CPIc 2013) in the UK. As BIM implementation requires synergy among various multi-disciplinary actors (Sackey et al. 2014), there is additional scope for observing inter-organizational BIM implementation in projects (Taylor and Bernstein 2009). After all, projects are excellent vessels to implement and study innovations (Shenhar et al. 1995), because any successful innovation relies on a sound project (Shenhar and Dvir 2007). Drawing upon the above, there are three levels of observing BIM: market (macro-), inter-organizational (meso-), and intra-organizational (micro-level). This paper aims to explore understand the relation between BIM adoption motivations (micro-level) and BIM implementation (meso-level) within the context of project networks (macro-level). From a practical perspective, this is important because firms still struggle adopting and implementing BIM. Theoretically, this work aims to shed new light on construction innovation, using BIM as a research setting. Accordingly, it links these levels to reach a comprehensive understanding of BIM innovation adoption, implementation and diffusion, using the concept of loosely coupled systems.

This study extends the online survey study of Cao et al. (2016) who unraveled a relation between BIM adoption motivations and implementation practices across design organizations, by here studying three multi-disciplinary project networks (cases). This study explores the relation between intra-firm motivations (*heterogeneity* attributes) for adopting BIM innovation, and how innovation unfolded and was applied (implementation) in projects, at a network level (as *systemic* innovation), drawing upon empirical data from three cases. Subsequently, the study attempts to link the intra- and inter-organizational levels of BIM, by confronting BIM motivations with BIM practice. The study is organized as follows. First, the theoretical basis around innovation, BIM, and network view of BIM innovations is presented. Subsequently, the selected methodology and data collected are presented. The paper ends by presenting, interpreting and confronting empirical data against literature, outlining implications for research, practice and policy, before concluding with summary and future directions.

Theoretical basis and knowledge gap

Innovation diffusion in construction industry

Rogers' (2003) diffusion of innovations model describes the process by which innovations spread via communication channels across social systems over time. Some innovations spread relatively rapidly while other innovations spread slowly depending on (a) novelty, (b) compatibility with existing values, beliefs, and experiences, (c) easiness to comprehend and adapt, (d) tangibility, and (e) testability (Rogers 2003). Real-life phenomena do not unfold in a linear, but instead a highly complex, inter-related and complex manner. Similarly, innovation diffusion is multi-scalar and complex. Local networks' interactions (micro-level) trigger the emergence of global structures and behaviors (macro-level) (Rogers et al. 2005). Within organizations, the innovation decision-making process consists of five stages, initiating it from the (1) agenda-setting of innovation and its (2) matching to the overall organizational agenda, followed by the implementation of innovation through iterative cycles of (3) redefining/restructuring the innovation, (4) clarifying its relation to the organization and (5) routinizing it into the organization's ongoing activities (Rogers 2003).

Given that even firms delivering similar services or products are highly heterogeneous; repetitive and heterogeneous micro-scale behaviors and adoption decision contribute to macro-scale phenomena, and diffusion (Rogers et al. 2005). Construction is a largely project-based industry (Morris 2004) and construction projects are unique by displaying high demand and supply variability. Thus, projects, upon which construction industry is organized, are highly heterogeneous and complex. For Rogers et al. (2005) heterogeneity is central in the diffusion of innovations theory, and probably acknowledging the influence of heterogeneous institutional contexts on macro-scale phenomena is a promising way forward for grasping innovation in construction and particularly complex project networks.

Historical review of Building Information Modeling

Projects are nexuses of processing information (Winch 2002). Presently, BIM is considered the most representative information aggregator in construction. BIM is not only a domain of digital artefacts, but has historical roots in the long process of structuring and standardizing building information for construction projects (Laakso and Kiviniemi 2012). Whereas the term BIM was introduced in 1992 (van Nederveen and Tolman 1992), its underlying principles were not entirely novel for construction. BIM has evolved from efforts for structuring and consistently representing information and knowledge about building artefacts, which was a predominant line of thought in the 1970s (Eastman 1999), under the term '*building product model'*.

Around mid-1980s, initiatives in the USA for '*building product model'* definitions were developed for exchanging building information amongst Computer-Aided Design (CAD) applications (Eastman 1999), replacing error-prone human interventions. Building product modeling advancements followed the long-standing debate on the computerization and digitalization of construction (Eastman 1999). Industry Foundation Classes (IFC) is probably the most popular and long-lived data exchange format for construction and is supported from various commercial BIM applications. Against widespread belief, BIM is not completely newly-found, but the result of evolving efforts by industry consortia to structure building information (East and Smith 2016) in building product models.

Whereas BIM is a relatively old concept from a product modeling perspective, it could be still branded as an innovation for construction, as although its content is already known to lower-tiers actors of the supply chain, implementing it in projects from all actors is something entirely new. The need for aligning BIM with numerous processes, standards, protocols and workflows is novel and thus, an innovation. BIM is an evolving concept and scholars and practitioners move towards more broad descriptions of BIM, such as ‘Building Information Management’ (Becerik-Gerber and Kensek 2009), “digitally-enabled working” (Dainty et al. 2017) and digitization (Morgan 2017), to capture numerous associated innovations. Additionally, BIM-related policy is also considered innovation. Its novelty lies at policies prescribing BIM-related contract addendums and workflows in project delivery. Table 1 summarises the afore-described key studies that contributed to the evolving nature of BIM.

<<Insert Table 1 around here>>

BIM is seen as a “*multifunctional set of instrumentalities for specific purposes*” (Miettinen and Paavola 2014) that affects various actors across construction lifecycle, while policies, processes, and technologies interact to generate a digital building design (Succar et al. 2012). Loose coupling in computer and system design entails components that are not constrained in same definitions, programming languages, environment (web or desktop) operating systems, or platform. Therefore, BIM is a domain of loosely coupled Information Technology (IT) systems for generating, controlling, and managing information flows intra- and inter-organizationally. This is in contrast to reports of tight technological coupling of BIM shared models (Dossick and Neff 2010). Indeed, the state-of-the-art of BIM technology has not allowed to work past the concept of reference models (Berlo et al. 2015) or the limitations of asynchronous collaboration (Cerovsek 2011).

Undoubtedly, BIM not only affects the representation of building product information, but also how actors of multi-disciplinary project networks collaborate (Bryde et al. 2013; Dossick and Neff 2010; Taylor and Bernstein 2009). Thus, whereas it is a technological innovation, BIM has been linked not only to coordination of technological artefacts, but also complex socio-technical processes to align heterogeneous actors and information (Liu et al. 2016; Sackey et al. 2014) across projects, networks, and markets. Accordingly, whereas BIM adoption relies on intra-firm decisions, its implementation depends on inter-firm collaboration and coordination.

BIM innovation adoption, implementation and diffusion

Various industry players are drawn to BIM and it inevitably becomes object of high quality scientific research. Currently, BIM research develops in three categories: (a) *adoption* of isolated firms, based on individual of discipline-specific perceptions, (b) *implementation* in projects, based on case studies, and (c) *diffusion* at a macro-level, focusing on distinct countries. To illustrate this categorization, Table 2 presents an indicative list of BIM research streams. BIM adoption studies provide rich insights into intra-firm barriers and enablers. Son *et al.* (2015) and Lee et al. (2013) analyzed BIM adoption in architects in China using Technology Acceptance Models (TAM) and updated TAM respectively, and individual perceptions and mistrust were key barriers. Both relational and technical aspects shape the transformation of contractors in the USA for BIM adoption (Ahn et al. 2015). As adoption relates to micro- and diffusion to macro-scale, implementation relates to an intermediate or meso-level. Similarly, technical and organizational BIM implementation studies offer a firm grasp of BIM advantages and shortcomings. Such studies identified benefits in design management (Elmualim and Gilder 2014), project management, communication, and coordination improvement (Azhar 2011), project performance (Bryde et al. 2013), collaboration, and coordination (Dossick and Neff 2010).

<<Insert Table 2 around here>>

Surprisingly, most BIM adoption or implementation studies, do not approach innovation from a network level. BIM diffusion studies facilitate better understanding of how BIM innovation unfolds across contexts, and whether the innovation is evolutionary or revolutionary (Burns and Stalker 1961). Succar and Kassem (2015) described BIM implementation as a '*three-phased approach'* that includes readiness, capability, and maturity that firms should develop to successfully use BIM. In projects with various BIM-using firms, implementation varies greatly, as firms carry different BIM readiness, capability, and maturity levels, due to their heterogeneity and different sizes (Succar and Kassem 2015; Succar et al. 2012). Succar and Kassem (2015) categorized BIM diffusion dynamics into *top-down*, *middle*-out, and *bottom-up*, depending on the type of pressure, i.e. downwards, horizontal, or upwards, received by government, large firms, or small firms respectively. Correspondingly, a network-view of projects offers a rich contextual setting to study BIM innovation.

Systems and innovation

This paper studies BIM as a construction innovation, from a systems' perspective. Systems Thinking emerged soon after World War II and offered a constructivist approach to the positivism of operations management research (Klir 2001). Klir (2001) defined a system as a set of things, *thing-hood*, and a set of relations among these things, *system-hood*. The term *system* is usually used interchangeably with the term *network*, however the latter, is a newer term than that mostly relates to the representation of a set of things (nodes) and a set of relations (links). The AEC has also been described as a 'loosely coupled system' (Dubois and Gadde 2002).

This study adopts Orton and Weick's (1990) dialectical definition of *'loosely coupled system'*. Accordingly, such a system is both closed and open to outside forces, as its constituent elements display both distinctiveness and responsiveness (Orton and Weick 1990). A 'loosely coupled system' is neither a 'managerial failure', nor needs to be transformed into a tight system, but instead entails tools for understanding and evaluating interpretative systems (Orton and Weick 1990). Conversely, a tight system would be static and possess neither distinctive nor responsiveness. Drawing upon the above, studying loosely coupled systems facilitates the understanding of "fluidity, complexity, and social construction" of organizational structures (Orton and Weick 1990). In the context of construction, indeed projects are extremely complex and inter-firm relations are fluid, by maintaining both distinctiveness and responsiveness. Chesbrough and Teece (1996) distinguish between autonomous and systemic innovations, as the former can be pursued independently by firms in a decentralized way, whereas the emerging inter-relations in the latter, suggest an additional need for control.

Brusoni and Prencipe (2001) suggest that varying cooperative agreements such as market-based, joint ventures, and strategic alliances need coordination and integration to safeguard the responsiveness needed in the loosely coupled system. In systemic innovations, there is an additional need for coordination, which is usually covered by highly integrated firms who can leverage their size. Such firms are called systems integrators and are both specialized in in-house activities and, keen to manage technological capabilities of other firms in the network (Brusoni and Prencipe 2001). In similar spirit, Dhanaraj and Parkhe (2006) discuss recruitment and brokering potential of *'hub firms'* in order to coordinate – or orchestrate – innovation in networks of firms. They recognized the focal role of the orchestration/hub firm – whose role resembles that of a system integrator – and the importance of three interdependent parameters among the multi-actor network: (a) knowledge mobility via formal and informal communication channels, (b) innovation appropriability by capturing benefits from innovation via trust and mutuality and (c) network stability through subtle leadership, recruitment and brokering activities (Dhanaraj and Parkhe 2006). However, given the high actors' heterogeneity in construction networks, probably a less focal view would be a promising way forward to understand BIM innovation in multi-actor construction networks. The project actors' heterogeneity is characterized by six attributes: (a) goals, (b) knowledge bases, (c) capabilities and competences, (d) perceptions, (e) power and position, and (f) cultures (Corsaro et al. 2012). There is additional scope for studying BIM as a systemic innovation, through the lens of loosely couple systems from a non-focal perspective. Consequently, this study is agnostic concerning which actor would act as systems integrator.

Network view of BIM innovation

As an innovation, BIM is better pursued in a decentralized manner (Aibinu and Papadonikolaki 2016; Eastman et al. 2008) and it is thus a systemic innovation. For Brusoni and Prencipe (2001), "*systemic innovations can be realised only in combination with complementary innovations*". Indeed, changes in procurement and particularly integrated schemes such as Design-Build (DB) have been suggested as necessary for BIM (Eastman et al. 2008). De Valence (2010) proposes that non-traditional procurement schemes, focusing on build and maintain encourage innovation through long-term engagements.

This study adds to the knowledge base of BIM adoption and implementation from a socio-technical view (Sackey et al. 2014). Sackey et al. (2014) used an actor-network lens to highlight the need for additional alignment and stability in BIM-using networks. Relevant past research on BIM implementation has focused on analysing the coordination needed in BIM-based work (Dossick and Neff 2010; Whyte and Lobo 2010). As opposed to previous work from a project network perspective, e.g. by Taylor and Bernstein (2009), Dossick and Neff (2010), and Papadonikolaki et al. (2017), this paper holds a dialectic perspective on inter-disciplinary teams' interaction in BIM-based projects, using a qualitative approach. The paper studies BIM adoption and implementation from an inter-firm (network) perspective and poses the following research questions (RQs): *How do intra-firm decisions about BIM adoption influence the implementation of BIM innovation in multi-actor project networks (RQ1), and in turn project* *outcomes (RQ2)?* Figure 1 illustrates the theoretical framework linking key themes of the paper to the RQs.

<<Insert Figure 1 around here>>

Methodology and methods

Research rationale

Following on the research question presented above and the theoretical framework in Figure 1, this study has two main objectives. The first objective is to understand the relation between BIM innovation adoption (micro-level), i.e. intra-firm motivations for BIM adoption, and BIM innovation implementation (meso-level). The second objective is to understand the relation between how BIM was implemented in project and how project participants perceived the projects' outcomes. The study holds an interpretative approach and explores the relation between BIM adoption and implementation using inter-organizational perspectives from various actors regarding BIM. The interpretative paradigm is consistent to the theoretical lens of the study, given that Orton and Weick's (1990) dialectical definition of 'loosely coupled system' encourages interpretation and dialogue with the data collected about the studied phenomenon. Consequently, case studies were selected as a suitable methodology to "*preserve dialectical interpretation*" (Orton and Weick 1990) and offer insights into the relation between BIM adoption and implementation.

The research context (macro-level) is crucial for understanding how BIM innovation is adopted and implemented (see Figure 1). After all according to Rogers (2003), innovation diffusion is a context-laden process through channels of communication, time and social systems. Before explaining the methods used, an analysis of the social system and research context are crucial for the methodological underpinning. The study took place in the

Netherlands, where BIM has gained a lot of traction the last decade. The idiosyncrasy of the Dutch market could potentially allow for generalization. As Dutch firms are keen to collaborate (Winch 2002) and seek consensus, any lessons-learned from this small market could reflect trends to other construction markets in Europe. The Dutch BIM maturity level is well-advanced, without being subjected to mandatory policies and external forces imposed by the Dutch government (Kassem et al. 2015). Instead, there is an abundance of 'bottom-up' initiatives for diffusing BIM in the Netherlands, as various firms from the industry co-create processes and standards to facilitate BIM implementation (Berlo and Papadonikolaki 2016). As a social system (macro-level view, see Figure 1), the context of the Netherlands offer a relatively stable research setting as it has a long-standing innovation culture (Dorée 2004).

The overarching research method was case study used to analyse the phenomenon in "*real-life context*" (Yin 1984) with the aim to provide a rich description and findings congruent with reality (Merriam 1998). The research methods used were qualitative and the epistemological paradigm followed interpretative (Merriam 1998). Three cases were selected from a larger pool of projects for being representative of the Dutch construction market. The unit of analysis of the cases was the project, as innovations are better observed in projects (Shenhar et al. 1995). Namely, all cases included multi-functional and housing typology, the dominant building project type in the Netherlands. Case A was a prestigious project, as it featured a complex design of three (irregular shaped) volumes organized around a public square with access to a canal and featuring underground parking. Case B was also a prestigious and quite unique project, as it concerned 12-floor housing towers over a pre-existing shopping arcade constructed in the late 1980s. This project (phase B) followed the construction of another housing tower a couple years ago (phase A). Case C was a rather mainstream project, featuring 44 apartments organized in two rectangular volumes in a densely populated area in the Netherlands.

The sample was diverse, as the participating firms were of varying sizes, e.g. Small-Medium Enterprises (SME) and large firms. The firms that participated in the projects (cases) were simultaneously engaged in long-standing project networks (alliances) and this ensured access to multi-disciplinary interviewees and facilitated the network-view of the study. The researcher was not affiliated with any of the participating firms. The cases (projects) were studied over a period of 18 months, during Definitive Design phase, Pre-Construction phase, and the first stages of Construction. Table 3 includes some descriptive characteristics about the projects and Table 4 data sources about the cases and details about interviewees.

<<Insert Table 3 around here>>

<<Insert Table 4 around here>>

Data collection and analysis

The primary data were 31 interviews with various actors per project from both supply and demand sides of the network and from multiple tiers, e.g. first-tier: client, contractor, architect, engineers, and second-tier: subcontractors and suppliers. After all, Creswell (1994) has put forward the idea of combining and triangulating among different sources of data to enhance research accuracy. Similarly, Gorard and Taylor (2004) have challenged the dominance of monothematic research methods and suggested instead the synthesis of findings from a triangulation of methods. Interviews were held at three study phases: (a) beginning of the study, (b) project progression, and (c) study validation, after the preliminary case analysis took place. Accordingly, the interview questions revolved around (1) the firms' motivation for adopting BIM as an innovation, (2) their perceived benefits and challenges during BIM implementation, and (3) the projects' outcomes. As usually cases study methods "*incorporate a number of data gathering measures*" (Berg 2001), the research also included secondary data for triangulation and credibility (Miles and Huberman 1994). Meetings observations, 'living labs', document (physical and digital) inspection, site and firm visits, and press coverage from online resources complemented the analysis of BIM implementation with additional sources and triangulate the findings.

The primary data (interviews) were analyzed using systematic thematic analysis, following the themes identified in the 'Theoretical background' section, around motivation for BIM adoption and an inter-organizational perspective. The interviews were audio-recorded, then transcribed and translated (from Dutch from native speakers). Both descriptive and '*in vivo'* coding was used to analyse the data. The secondary data were used to represent and analyse the BIM implementation process at project- and inter-organizational levels and triangulate, support, challenge or enrich, according to Miles and Huberman (1994), the insights into BIM implementation. Primary and secondary data were subsequently confronted to identify gaps between the motivation for BIM adoption and the actual BIM implementation, by drawing upon metrics of BIM maturity. These metrics included evaluation of the BIM-based collaboration process, which is seen as both prerequisite and indicator of the popular UK BIM Level Two maturity.

Data and Findings

The Data and Findings section has been divided in to three subsections that are presenting the data on: (1) BIM innovation adoption drivers across firms, (2) BIM implementation approaches across cases and (3) outcomes of the BIM-based projects. The first and second subsections present the data to answer the first research question based on the independent and intermediate variables (RQ1, see Figure 1). The third subsection presents the data pertinent to the second research question based on the dependent variables (RQ2, see Figure 1). The answers to both questions are given in the Discussion section.

BIM adoption drivers across firms

Because the cases were approached as networks of actors organized around projects, a systematic approach to analyze the three cases was followed. Actors from each case were interviewed separately about their intra-firm motivations for adopting BIM (Table 4). To ensure internal data validity, additional perspectives from various hierarchical levels (Eisenhardt and Graebner 2007) of the firms were received. In some instances, this approach was an opportunity to identify incongruent perceptions (Merriam 1998) and motivations about BIM adoption and implementation within the boundaries of the same firm. Overall, the data showed that BIM is indeed regarded as a novelty for construction from key actors but for varying reasons. Data presented in this section are related to the independent variables and RQ1 (see Figure 1).

Almost all actors of Case A adopted BIM driven from market demand (external driver). In the contractor's firm, it was recently decided "*that all projects must go in principle in BIM because that is the future*" (Case A-Contractor-BIM Coordinator). However, at that particular project, BIM was simply a contract requirement from the client. This decision had cascading effects upon the rest project actors. In the structural engineering firm, they acknowledged that "*BIM improves the process, but the advantage of BIM is for the contractor*" (Case A-Structural-Director) and they admitted that they "*switched to BIM because of the demand*" (Case A-Structural-BIM Modeler). According to the mechanical engineers the BIM benefits were: "*in the automation process (..) that makes it very clear to all parties (...) and its (BIM) adoption came from the market*" (Case A-Mechanical-Project Lead). The suppliers stated that: "*we are looking on how to do it (design) with 3D. The client started asking us for BIM. This was decisive for us working with BIM. This is the bigger influence of why we did it. But we also see benefits for our process*" (Case A-Supplier-BIM Engineer). However, the architects' decision to adopt BIM had different motives. Case's A BIM Modeler in the architect's firm shared: "*we were* *already relatively early engaged with BIM in our office, with discovering the capabilities of the software. One of the bosses, even from his studies, began with software development, so he has always some kind of love or interest in that and (...) we go along with it to see if it offers added value or not*".

The Case B actors were more strategic about BIM adoption decision-making. At least three of the main actors adopted BIM to improve their businesses and not to comply with market or client demand. The project client did not require BIM. The contractor shared: "*the most important aspect of BIM is consistency, which we share with all our partners towards the execution*" (Case B-Contractor-Site Engineer). Similarly, the architects acknowledged: "*for us it is not more expensive to model BIM than using 2D drawing, because our quality has gone up*" (Case B-Architect-Lead Architect). The structural engineering firm presented the most gradually developed approach to BIM adoption over the years. They shared that: "*for us in 2007 there was the main motivation to step to 3D design and BIM from the 2D design because we ourselves saw benefits. It was obviously a new development. And we ourselves discovered that there's a future in it, but we also saw from our own work benefits to better understand construction*" (Case B-Structural-Lead Engineer). In the mechanical engineers' and the subcontractor's firms, it was stated that BIM "*was requested from the market"* (Case B-Mechanical-Director). From the subcontractor it was stated: "*BIM is what the contractor demanded. They said, we are going to do this and our suppliers must join*" (Case B-Subcontractor-Project Leader). For the suppliers, the traction that BIM recently gained was a catalyst for adopting it. They explained that: "*four years ago we switched to 3D models to go along with modernity. The customer can better see what he gets. The errors can be discovered quickly*" (Case B-Supplier-BIM Modeler) and "*BIM is better for clients and goes with the times*" (Case B-Supplier-Director).

The Case C actors held incongruent positions as to what drove their BIM adoption decision-making. The client admitted that although they did not use BIM, they responded to the general market demand. They shared that: "*we want our partners to (use BIM), to increase their product quality*" (Case C-Client-Tender Manager). In the contractor's firm, they recognized that "*do BIM even if it is not a client requirement*" (Case C-Contractor-BIM Director). According to the Tender Manager of Case's C contractor: "*BIM is the business of the future; it is efficient and eliminates extra costs*". The contractor firm has founded a 'BIM Center' to disseminate BIM knowledge across various firm subsidiaries. Similarly, the architects' firm stated: "*BIM is very important for quality management (...) not all firms have realized what it can do to them*" (Case C-Architect-BIM Architect). However, the structural and mechanical engineering firms simply complied with market demand for BIM implementation in projects.

The data analysis revealed three main motivations for BIM adoption across the firms: (1) intra-firm strategy, (2) project-based requirements, and (3) market or client demand. First, intra-firm strategy pertained to the internal decisions across the firms to adopt BIM as a way to modernize their information management and computer-aided design infrastructure (all cases). Second, project-based requirements were short-term requirements that were project-specific and usually pertained to clients' demand for BIM adoption (Case A). Finally, general market demand stemming from institutional and industry prescriptions was a long-term motivation that contributed to firms' competitive advantage and factored to their decision on adopting BIM (all cases). From these three motivations, the first could be codified as *'internal'*, whereas the other two as *'external'*. Table 5 assigns the *'internal'* and *'external'* motivations codes (descriptive and in vivo) to the three project networks (cases).

<<Insert Table 5 around here>>

BIM implementation in project networks

From the above, BIM adoption depended on various internal or external intra-organizational motives (micro-level). However, BIM implementation is a collective inter-organizational exercise (meso-level) in applying technologies that fall under the umbrella of BIM domain. Data presented in this section are related to the intermediate variables and RQ1 (see Figure 1). Given that BIM has been approached as a domain of technologies, processes, and other functionalities in this paper, Table 6 summarizes key features of BIM implementation in the three cases, as derived from document analysis and meeting observations and naturally, each BIM implementation process was unique across the studied cases.

<<Insert Table 6 around here>>

Following the study's theoretical lens, BIM implementation in the cases was explored by content analysis of the interviews around: (a) communication channels, (b) trust, and (c) network stability activities (Dhanaraj and Parkhe 2006). In Case A, BIM capabilities were a decisive factor for *communications* quality. Case's A Design coordinator from the contractor stated: "*simply each party is differently able to implement BIM. And that is sometimes difficult. (...) The communication was always difficult*". For other actors, the BIM-based collaboration was not participatory, but formal and top-down instead. The BIM Engineer of Case's A supplier shared that: "we *have not gone in clash sessions. The contractor has done it themselves and then send us the findings. Sometimes we sit with some specific suppliers on the table and discuss, but usually we receive a mail or phone call. (...) This process is exactly the same with other contractors*". Naturally, this way of communication had repercussions for *trust*. The Design coordinator of the contractor stated: "*the collaboration and how one must work with BIM and the expectations of each other should be well-pronounced, in order to trust each* *other*". According to Case's A Mechanical Engineer's Project Leader, due to BIM they needed "*also a trust bond to build with the contractor (...) a bit of mutual trust towards each other*". Regarding *network stability* activities, there were disparate approaches and not a clear vision. On the one hand, the Architect admitted that: "we *do not really have a role distribution within the office. Everyone does it all (...) we do not really work with terms like BIM manager*". The structural engineers said that they: "*only work in BIM when the architect or the installer in BIM work too*" (Case A-Structural-BIM Modeler). The mechanical engineers said they "*always choose a contract initially, not parties*" (Case A-Mechanical-Project Leader). On the other hand, the suppliers were more strategic regarding BIM adoption. They shared that "*with other contractors we also use BIM. But not all their partners can do it with BIM. (...) We need permanent contact persons to have in the partners (otherwise) you cannot do good BIM*" (Case A-Supplier-BIM Engineer). From the above, in Case A, the network struggled to align communication with trust and were not strategic in network formation for BIM implementation.

The Case B contractor ensured with formal and informal approaches that BIM *communications* run smoothly. Case B Contractor's Site Engineer argued that: "*we make appointments in advance. We have a BIM kick-off meeting, where we go with all our partners to agree how we are going to provide, what sessions we're going to get to keep our noses in the same direction for BIM*". The architects also often contributed in good communications. They explained: "*we also sometimes took the role of 'BIM runners'. That is not always good, but we did that because we had to meet the deadlines*" (Case B-Architect-Lead Architect). This was seconded by the Tender Manager of the Mechanical engineering firm who shared: "*all partners sit around the table to highly structure on a daily basis what needs to be done to make everything run smoothly so that the costs of failure are minimum*". The subcontractor acknowledged that because of the dense communications they "*gain more knowledge of the problems of other parties*" (Case B-Subcontractor-Project Leader). Undoubtedly, this would in turn benefit *trust*. The architect admitted that there is a lack of trust towards their profession and shared that: "*our customers and clients have not yet confidence in the construction industry, because of the mistrust. (...) So if we are open about what we want to make, then we get another discussion*" (Case B-Architect-Lead Architect). For the contractor, both formal and informal communications were beneficial for knowledge externalities. The contractor's Site Engineer explained the benefits of alliancing and BIM use from their partners as follows: "*we look in the 'kitchen' of other contractors. (...) This is why we have also an open BIM structure, so that we do not impose how our partners should work*". The network had trusting and long-term relations, e.g. the structural engineers considered themselves the contractor's "*house builder*" (Case B-Structural-Lead Engineer). All the above contributed to a more *stable network*, although there were both opponents and proponents of out-sourcing BIM services. For example, the Mechanical Engineering firm shared that: "*I think we are fairly neat because we do not out-source BIM*" (Case B-Mechanical-Tender Manager), whereas the subcontractor firm adopted the opposite strategy. The Project Leader of Case's B subcontractor shared: "*we have permanent BIM drafting company that we work together. We sit together in one office so we have two separate companies, but we do everything together*". Thus, in Case B, good network communications and trust supported any heterogeneous decisions on BIM adoption and implementation.

In Case C, the *communications* were organized in a top-down manner, essentially via the contractor. They explained that they have been using their "*BIM Center to train the subcontractors and suppliers (...) and perform analyses to coordinate BIM models from all suppliers*" (Case C-contractor-BIM Director). The suppliers and subcontractors only used an extranet for 'data drops' to exchange information. However, because in this project, not all available BIM functionalities for collaboration were used, the various actors did not have a lot of interaction. This naturally, had implications for *trust* and *stability* in the network. According to the architects: “*we have to develop our BIM collaboration methodology all the time (...) because all the partners are also changing their methodology*” (Case C-Architect-BIM Architect). These ad-hoc communication patterns, caused mistrust in the project team. The contractor was trying to control mistrust by direct confrontation: “*we always asked them how they stand and if they were ready to show us all the cards*” (Case C-Contractor-Tender Manager). Regarding *network stability* activities, the contractor was trying to select project partners based on BIM-savviness. They shared that: “*we get our suppliers to enter our BIM contract (protocol)*” (Case C-Contractor-BIM Director). This was in accordance with the client who stated: “*we require that our partners use BIM to improve the design and minimize design faults (...) because we have a culture of young people and innovation in order to offer excellent services*” (Case C-Client-Tender Manager). However, these visions were not supported by any formal or informal structures, neither were democratized across the rest of the project network.

Outcomes of BIM-based projects

Drawing upon the interviews during the projects’ progression (Phase b) and the validation sessions of the preliminary findings with the interviewees (Phase c, see sub-section “Data collection and analysis”), insights into projects’ outcomes were obtained. The validation sessions aimed at grasping the reflections of key case participants about the projects’ outcomes. As opposed to the initial interviews, the validation sessions were collective interviews, featuring key project participants, in the form of ‘living labs’. They were an opportunity for reflection on their project and particularly regarding BIM. This mixture of methods induced communicative validity (Sarantakos 2005) by involving the participants to check the accuracy of data and add depth and richness to the data. After all, Merriam (1998) has previously acknowledge the need to increase the validity of case study methods. These sessions took place only for Case A and Case B, and not in Case C, because those interviewees were unavailable as they have since moved to new firms. The discussions in the validation sessions revolved around whether the projects were delivered on time and budget, about successes and failures in the projects and lessons learned and motivations for change in subsequent projects.

Case A project was completed in good order and on time. However, not all initial project aspirations were fulfilled, probably because there were incongruent BIM motivations (external or internal) within the project network. For example, they did not manage to optimize and control the logistics in site using BIM-based methods, as planned at the beginning. Regarding their aspiration to deliver 'as-built' BIM models to the facility management organization, this took place as planned, but they still face challenges into streamlining this information for facility maintenance. Regarding their BIM-based collaboration, they contractor firm admitted that '*the communication was not very good'*. Overall, their varying firm sizes and BIM capabilities were a limitation for executing this project, e.g. the architect's firm was understaffed to manage the complexity of such a prestigious and unique project for the Dutch standards.

Case B project was also completed on time. As the project was part of a larger investment, the project network was awarded continuation in the next project phase (phase C). The project network perceived this as a recognition of their successful BIM adoption and implementation outcomes. Given that the client hired the same network (alliance) was considered an indication that the project progressed well and that their compatible BIM motivations were effective. The third phase of the project is currently under development and includes a new housing tower. Additionally, there are also new discussions of a project fourth phase to be expanded to a neighboring site with a new tower consisting of more storeys and more apartments (phase D-107 apartments). Regarding, their BIM-based collaboration, the project actors admitted that they improved their BIM capabilities immensely through these repetitive projects. However, they stressed that although the design was similar, the design preparation was the opposite of ‘copy-paste’, as with the advent of BIM-related technologies, they were continuously amending their BIM implementation and collaboration processes.

Case C project was also delivered on time with no delays, similarly to the other two. However, it was not possible to evaluate the outcomes of this case, as the contractor’s organization became insolvent since then. Afterwards, the contractor firm re-evaluated their strategic objectives and priorities, which among others, featured the application of lean methodologies, BIM, and supply chain management, and underwent major restructuring in personnel. Essentially all the interviewees from the contractors’ firm have since moved to different companies. Therefore, although the project was completed satisfactorily, there was no opportunity to reflect on the future of Case C’s network and the outcomes of this BIM-based collaboration remain largely inconclusive. This is naturally a limitation, but also probably an indication of the project’s outcomes.

Discussion

BIM innovation from micro- to macro-level

The AEC behaves as a ‘loosely coupled system’ (Dubois and Gadde 2002), given that it is fragmented into various collaborating or competing firms. Essentially, also BIM could be described as a loosely couple system due to its varying flexibly interconnected functionalities. For systems thinking, a system is loosely coupled when its actors have or use little or no shared knowledge, understanding, and visions with the other multi-disciplinary actors – that is *distinctiveness*. Loosely coupled systems allow thus for interactive interpretation and shared social construction meaning when needed (Orton and Weick 1990), as opposed to a tight system that would be static and unresponsive. Throughout the three cases, the actors were complying with varying external or internal drivers when deciding to adopt BIM innovation. These drivers ranged from matching market demand (macro-level), what Bossink (2004) refers to as '*environmental pressure'* (Case A-external) to business growth aspirations (Case C-external) to increasing quality (Case B-internal) (micro-level) (Table 5). However, loosely coupled systems are also potentially useful for diffusion, as they are *responsive* (Orton and Weick 1990). Compatible internal or external motivations for BIM adoption across firms result to more collaborative BIM implementation in projects (answer to RQ1).

Among the three cases, Case B could be considered more responsive than Case A and Case C, as they did not have rigid BIM-based partner selection criteria, but were flexible regarding meetings and co-locations (Table 6). Instead, in Case A, although the BIM implementation processes were consistent with firms' 'external' BIM adoption drivers, they were far too rigid and did not allow for systems' responsiveness. In Case C, the again consistent firms' 'external' BIM adoption motivations were not supported by any collaboration structure for BIM implementation (Table 6). To increase construction performance, various scholars "prescribe either more competition or more cooperation to increase the performance of the industry as a whole" (Dubois and Gadde 2002). Indeed, Case A and Case B were more collaborative, whereas Case C displayed a competitive and unshared attitude to BIM implementation. Accordingly, investing and engaging in a collaborative attitude to BIM implementation in projects indicated satisfactory project outcomes, consistent with scope (answer to RQ2).

Undoubtedly, BIM implementation immensely impacts collaborative design and engineering. Kvan (2000) highlighted that collaborative design is also a 'loosely coupled system,' which is time-consuming and requires relation management among involved actors. De Valence (2010) puts forward the idea that "*the best way to increase innovation lies in the methods and systems used to procure building and construction projects*". Therefore, enabling structures, such as relation management and special procurement routes are needed for maintaining both firms' *distinctiveness* and system's *responsiveness*. Regarding BIM innovation adoption, aligning BIM adoption decision-making with BIM implementation not only supports the latter, but also instigates closer collaboration and synergy among the multi-disciplinary actors (Sackey et al. 2014). While BIM adoption is an inter-firm decision, whether BIM adoption drivers are external or internal, predispose the way that the project network implements BIM and outlines their outcomes. Thus, encouraging key AEC actors (micro-level) to adopt innovations such as BIM in a long-term perspective that induces relational stability could actively support the coordination of BIM work (meso-level) and BIM diffusion (macro-level).

BIM project networks

Cross-case comparison of BIM adoption and implementation

The study revealed consistent patterns on the relation between project network composition, BIM adoption motivations and the level of BIM implementation. To this end, the role of key organizations in the BIM-using networks and their relation to Rogers et al. (2005) innovation decision-making process was a major influence on the sophistication of BIM implementation. Rogers et al. (2005) had explained how innovation decision-making process in organizations go through the stages of knowledge, persuasion, decision, implementation and confirmation or evaluation. From the cross-case comparison, the contractors of Cases A, B and C were at different stages of innovation adoption and specifically at implementation (Cases A and B) and persuasion stage (Case C). In a sense, the Case C contractor had not addressed the need for persuading its employees and supply chain partners in using BIM.

Namely, when the contractor adopted BIM as a part of their ‘internal’ vision, BIM implementation was more sophisticated by including various functionalities, and flexible by supporting collaboration (Case B, see Table 6). Contrariwise, in cases were the contractor was simply complying with the growing market demand for BIM adoption, without actively supporting it, BIM implementation was more ad-hoc as seen in Case C. Simultaneously, firms where the BIM visions were not well-diffused across all hierarchical levels (contractors of

Cases A and C), displayed inconsistent behaviors during BIM implementation. Thus, it can be stated that the composition of the BIM-pushing actors in the network outlines or even predicts the level (maturity) of sophistication that BIM would be applied with. Among these cases, the contractor might qualify as BIM *innovation change agent*.

BIM implementation unfolded in varying ways. On the one hand, Case A and Case B displayed sophisticated approaches to BIM implementation, by utilizing various BIM functionalities and relying on interoperable BIM tools and the exchange of open standards as prescribed from UK BIM Level 2 (GCCG 2011) (Table 6). Additionally, the firms operating in these two cases had generally compatible BIM adoption motivations; Case A adopted BIM due to largely 'external' motivations, whereas Case B adopted BIM driven from 'internal' motivations. On the other hand, Case C displayed less sophisticated or ad-hoc BIM implementation processes (Papadonikolaki et al. 2016), by combining digital and paper-based deliverables in hybrid practices (Harty and Whyte 2010) (Table 6). Similarly, the firms of Case C responded to both 'external' and 'internal' BIM adoption motivations and probably this hindered the BIM implementation process.

Structure and organization of project networks

Loosely couple systems is a useful lens to understand both specialization – through in-house capabilities – and integration – through out-sourcing activities – of technological knowledge (Brusoni and Prencipe 2001). Dhanaraj and Parkhe (2006) recognized the importance of three interdependent parameters for innovation in networks: (a) knowledge mobility via formal and informal communication channels, (b) innovation appropriability, and (c) network stability through leadership, recruitment and brokering activities. First, with regard to *communication*, the firms that deployed various formal and informal communication channels performed better in managing BIM innovation (Case A and Case B). These outlets ranged from meetings, use of digital artefacts, and communication over online means (see Table 6). These outlets and artefacts show that indeed the BIM domain is also a loosely coupled IT system as well as the case findings confirmed relevant previous reports of ‘organizational loose coupling’ in BIM-using teams (Dossick and Neff 2010). Among the two cases, Case B additionally supported communication with informal and relational approaches that enriched and supported the implementation of BIM innovation (see quotations of Case A-Contractor-Design coordinator and Case B-Mechanical-Tender Manager). After all, proactive and informal inter-firm communications across multiple tiers, beyond contractual prescriptions could facilitate supply chain integration in project networks (Papadonikolaki and Wamelink 2017; Taylor and Bernstein 2009). Besides, Brusoni and Prencipe (2001) claimed that as loosely coupled systems are pervasive *“they will become even more important in future, as the continuing growth and specialization of knowledge production will make firms’ external knowledge relations even more important”* – essentially knowledge externalities. Indeed, ‘*knowledge externalities’* could facilitate the adoption and implementation of innovations (de Valence 2010).

As *appropriability* entails the capturing of benefits from innovation via trust and mutuality, it relates to innovation investment and ownership. Across the cases, firms used knowledge externalities to improve and develop their own BIM implementation process (see quotation of Case B-Contractor-Site Engineer). However, although the contractor of Case C made a rather large investment in a ‘BIM Center but they did not further disseminate BIM knowledge across their partners and innovation was not appropriated by partners, by creating a ‘silo’ of knowledge. The ambitious ‘BIM Center could be described as an effort to induce a ‘tight coupling’ in the system of Case C. On the contrary, the Cases’ A and B contractors were keen to share BIM knowledge with their partners, although they had not performed such considerable investment in BIM. Allowing the project partners to appropriate the benefits of knowledge might be an incentive to engage a larger part of the project network with innovation (de Valence 2010). Similarly, Baddeley and Chang (2015) after identifying factors affecting the uptake of BIM, concluded that emphasizing on collaboration benefits is probably more important than any traditional financial incentives.

According to Dhanaraj and Parkhe (2006), all knowledge mobility (via formal and informal communications), appropriability of innovation, and *network stability* are interdependent. Indeed, from the empirical data, BIM was a partner selection criterion in Case A and Case C (Table 6), and BIM-savviness affected the composition of the project network via recruitment mechanisms. However, in Case B there were both firms that our-sourced and delivered in-house BIM capabilities, but this did not hinder knowledge mobility and the network remained stable. This is in support of Brusoni and Prencipe (2001) that *"maintaining capabilities wider than the range of activities actually performed in-house is, under some circumstances, a necessary condition to effectively manage external relationships in the presence of technological change"*. To this end, the compatibility of BIM adoption motivations and knowledge mobility in Case B contributed to innovation success and lead to a stable – but loosely coupled – system. Dhanaraj and Parkhe (2006) previously suggested the theoretical and practical merits of testing the causalities between innovation output and network stability, and according to Case B; the former led to the latter. Contrariwise, in Cases A and C, any recruitment and network stabilizing activities hindered knowledge mobility across firms and did not manage to contribute to positive innovation outcomes.

Actors' heterogeneity

The various project actors unsurprisingly held rather diverse opinions and behaviors around BIM adoption and implementation. Even among same disciplines, motivations and behaviors differed (heterogeneity). Even firms delivering similar services or products are highly heterogeneous. Actors' heterogeneity is characterized by six attributes: goals, knowledge bases, capabilities and competences, perceptions, power and position, and cultures (Corsaro et al. 2012). Drawing upon the empirical data, the case projects' outcomes were influenced by various internal or external drivers for BIM adoption, as well as diverse behaviors during BIM implementation. Given the limited number of cases, no repetitive behaviors across disciplines were observed, but instead, between pairs of actors. First, the relation between client and contractor was decisive for the adoption of BIM innovation (Case A and Case C), which confirms similar findings by Cao et al. (2016). This partly supports Porwal and Hewage (2013) who after studying publicly funded construction projects, claimed that "*maturity and adoption of BIM depend mainly on the client or the owner*". Additionally, the relation between architect and structural engineer was critical, as these two disciplines are very important for the coordination and organization of BIM work during the design phases (BIM implementation). After all, primarily architects and subsequently engineers lead the generation of BIM-based information (Papadonikolaki et al. 2017). According to the empirical data, in cases where the architect and the structural engineer followed compatible BIM adoption drivers, communications and project outcomes were better (Case B).

Whereas this paper did not initially hold a focal view of construction and innovation and was largely agnostic in terms of the disciplines' dynamics, some observations about innovation leaders and change agents could be drawn upon the empirical data. After all, "*a central characteristic of loosely coupled networks is an in-house capability for systems integration*" (Brusoni and Prencipe 2001). Accordingly, the actors of the two afore-described pairs could qualify as 'orchestrators' of innovation, depending on the procurement routes and essentially their involvement. For example, a DB contract may provide the opportunity that the contractor plays a 'systems integrator' role, following clients' prescriptions (Case C). In traditionally procured projects, the relation between architect and structural engineer might be proven appropriate to manage the implementation of BIM innovation. However, as Dhanaraj and Parkhe (2006) stated, categorizing actors into '*orchestrators*' and '*peripheral*' "*may be an oversimplification, particularly in settings of high-density networks or small networks*". This suggests that there is additional room for exploring and understanding power dynamics in BIM-based projects.

Research implications

Practical implications

This study carries implications for construction management and engineering practitioners, as it has displayed an interdependence between the types of BIM adoption motivation – external or internal – and the maturity/level that BIM innovation is implemented in projects. Accordingly, although actors may appropriate innovation, the stability and performance of the network also depends on knowledge mobility via formal and informal communication channels. Similarly, corporate compatibility of BIM adoption drivers affects network stability by recruitment of BIM-savvy partners and through decision-making on delivering in-house or out-sourcing BIM services. These relations might support policy-makers in their decision-making about pushing BIM innovation across the industry. To this end, strict mandates for BIM adoption might hinder the effectiveness of BIM implementation, for not supporting the exploration of network-regulated BIM adoption strategies. Conversely, an incremental adoption of BIM functionalities and structures, such as file exchange formats, quasi-contractual means, platforms, and online data environments could increase BIM-based project outcomes. At an inter-organizational level, some propositions for networks that would engage in BIM implementation could be to:

(a) align intra-organizational BIM adoption motivations with inter-organizational BIM implementation process to utilise many BIM-related functionalities, and

(b) revisit and re-evaluate the relations between key actors of the project network: e.g. client-contractor and architect-structural engineer, depending on the procurement route.

Theoretical contribution

This research contributes to existing literature and knowledge base about BIM innovation, by exploring its adoption and implementation through the lens of loosely coupling. The study contributes to the knowledge of innovation from a network perspective. First, it explored the BIM innovation adoption motivations at a firm level and discovered that these may depend on internal or external drivers. However, as innovations are usually observed in projects (Shenhar et al. 1995), they do not only depend on one firm's goals (Sackey et al. 2014), but rather those of a network of firms. Accordingly, it unveiled a relation between intra-firm BIM adoption drivers and BIM implementation levels and revealed that in projects networks with compatible BIM adoption drivers, the implementation of the innovation is both sophisticated – by including various functionalities – and flexible – enabling collaboration. Corporate philosophy compatibility is a well-known factor of successful management of networks (Mentzer et al. 2001; Papadonikolaki and Wamelink 2017).

Second, this study also revisited the concept of 'loosely coupled systems' and offered new data to the framework of Dhanaraj and Parkhe (2006) on communication structures, appropriability, and network stability activities of BIM-using project networks. In the context of BIM literature, this study confirmed previous findings of 'organizational loose coupling' in BIM-using teams (Dossick and Neff 2010). Additionally, it shed new light on the nature of BIM domain as a loosely coupled systems, as opposed to descriptions of BIM as a tight coupled system (Dossick and Neff 2010) by presenting various functionalities of BIM implementation in Table 6. Additionally, approaching BIM as an evolving domain from a historical view (see Table 1) is an effort to acknowledge that it has emerged from a collaborative setting between industry and policy, and although its associated technologies are old, its novelty lies in the need for processes, coordination and well-defined workflows.

Finally, the study added to the knowledge base of BIM research by offering new empirical data on BIM adoption and implementation from a project network perspective. The study complemented past work by Taylor and Bernstein (2009), Dossick and Neff (2010), Sackey et al. (2014) and Papadonikolaki et al. (2017) but held a more dialectic perspective on how the interactions of inter-disciplinary teams co-create meaning in BIM-based projects (Papadonikolaki 2017). Also, this study approached the intra-firm motivations for BIM adoption from an analytical approach, using theoretical lens from Corsaro et al. (2012) on actors' heterogeneity.

Research limitations

The study took place in the Netherlands, and although it offered rich contextual insights into collaborating networks in BIM innovation, the case study research design naturally does not allow for full generalization (Merriam 1998). Nevertheless, the case study methodology provided a rich description of the phenomenon and allowed for a realistic representation of the challenges and opportunities that construction networks implementing BIM are facing. To this end, the Dutch construction market was a relevant locale to test newly introduced innovations, such as the adoption and implementation of BIM. This is because, whereas the market is small, it has a high rate of BIM adoption, framework (alliance) agreements, and possibilities for second-hand, or '*external'* BIM knowledge, also known as '*knowledge externalities'*. After all, the ubiquitous collaborative culture in the Netherlands has been proven to be independent of delivery methods, e.g. traditional or integrated (Koolwijk et al. 2018).

Moreover, the Dutch construction industry has been proven quite interdependent across policy and practice when it comes to adopting innovations (Bossink 2004). The overall applied consensus-seeking and collaborative culture of Dutch construction firms (Dorée 2004), could be considered apart from a research limitation, also a promising way forward for informing BIM-related policy-makers about how BIM adoption and implementation unfolds in practice. Accordingly, in the future, a cross-cultural case sampling might shed more light on the complex socio-technical phenomenon of BIM adoption and implementation, which increasingly gains traction globally. At the same time, given that the functionalities of BIM are continuously in a transition, a longitudinal study might also increase the understanding of how BIM innovation unfolds within AEC networks.

Conclusion

This study has sought to further refine the understanding of how BIM adoption drivers influence BIM implementation through the theoretical lens of loosely coupled systems. After analyzing three cases of project networks in Dutch construction, the empirical data displayed an interdependence between BIM adoption drivers – external or internal – and sophistication or maturity of BIM implementation, namely the utilization of varying functionalities. Essentially Case B, which featured firms with internal BIM adoption drivers, delivered better project outcomes than Case C. Project networks where firms were motivated by internal BIM adoption drivers, e.g. about increasing quality, implemented BIM collaboratively and flexibly, whereas projects networks that adopted BIM to comply with external (client or market) demand were rigid and competitive during BIM-implementation and hindered knowledge transfer. This creates implications for intra-firm innovation adoption decisions and confirms the importance of holding a network view of construction innovation. It also implies that organizations that are comfortable with BIM innovation, such as ‘innovators’ and ‘early adopters’ (Rogers 2003) are more keen to engage in innovation diffusion in networks.

Moreover, causalities between corporate compatibility of BIM visions across construction firms and networks with project outcomes were revealed. Like-minded ‘innovator’ firms are more likely to experience consistent project outcomes. Both Case A and Case B, which featured compatible BIM adoption drivers (external and internal respectively), had more consistent project outcomes than Case C, which was characterized by incongruent BIM adoption visions among project actors. Another important finding was about the relation between inter-organizational knowledge mobility via formal and informal communication channels, which contributed to network stability. Allowing a flexible structure of knowledge externalities (Cases A and B) had better outcomes than centralizing BIM knowledge in silos (Case C-contractor).

All the above, imply that intra-organizational decision-making that is not aligned with the project network, such as funding specialized BIM centers or opening new departments, induces skewed inter-organizational power dynamics and unstable project networks. Thus, there exists a trade-off between showing intra-organizational leadership in BIM innovation , firms' BIM adoption decision-making and attaining consistent and desirable project outcomes. The implication for construction managers and engineers is the need for further alignment of BIM visions across firms. Finally, the study adds to the knowledge base of innovation in construction systems and particularly BIM innovation. It sheds new light on the relation between formal and informal communication channels that support appropriability of innovation from firms, regardless any recruitment activities that can only structurally affect the composition and stability of construction networks.

References

Abernathy, W. J., and Clark, K. B. (1985). "Innovation: Mapping the winds of creative destruction." *Research policy*, 14(1), 3-22.

Ahn, Y. H., Kwak, Y. H., and Suk, S. J. (2015). "Contractors' transformation Strategies for adopting Building Information Modeling." *Journal of Management in Engineering*, 32(1), 05015005, 05015001-05015013.

Aibinu, A., and Papadonikolaki, E. "A comparative case study of coordination mechanisms in Design and Build BIM-based projects in the Netherlands." *Proc., Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016)*, CRC Press 435-443.

Akintola, A., Venkatachalam, S., and Root, D. (2017). "New BIM Roles' Legitimacy and Changing Power Dynamics on BIM-Enabled Projects." *Journal of Construction Engineering and Management*, 143(9), 04017066.

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., and O'Reilly, K. (2011). "Technology Adoption in the BIM implementation for Lean Architectural Practice." *Automation in Construction*, 20, 189-195.

Azhar, S. (2011). "Building Information Modeling (BIM): Trends, benefits, risks and challenges for the AEC industry." *Leadership and Management in Engineering*, 11(3), 241–252.

Baddeley, M., and Chang, C. (2015). "Collaborative Building Information Modelling (BIM): Insights from Behavioural Economics and Incentive Theory." *Report for the Royal Institution of Chartered Surveyors (RICS)*, Royal Institution of Chartered Surveyors (RICS), London, UK.

Bazjanac, V., and Crawley, D. B. (1997). "The implementation of industry foundation classes in simulation tools for the building industry." *Lawrence Berkeley National Laboratory*.

Becerik-Gerber, B., and Kensek, K. (2009). "Building information modeling in architecture, engineering, and construction: Emerging research directions and trends." *Journal of professional issues in engineering education and practice*, 136(3), 139-147.

Berg, B. L. (2001). *Qualitative Research Methods for the Social Sciences*, Allyn and Bacon, Long Beach, CA.

Berlo, L. v., Derks, G., Pennavaire, C., and Bos, P. "Collaborative Engineering with IFC: common practice in the Netherlands." *Proc., 32nd CIB W78 Information Technology for Construction Conference (CIB W78 2015)*, 59-68.

Berlo, L. v., and Papadonikolaki, E. "Facilitating the BIM coordinator and empowering the suppliers with automated data compliance checking." *Proc., Proceedings of the 11th European Conference on Product and Process Modelling (ECPPM 2016)*, CRC Press 145-153.

Bossink, B. A. (2004). "Managing drivers of innovation in construction networks." *Journal of construction engineering and management*, 130(3), 337-345.

Brusoni, S., and Prencipe, A. (2001). "Managing knowledge in loosely coupled networks: Exploring the links between product and knowledge dynamics." *Journal of Management Studies*, 38(7), 1019-1035.

Bryde, D., Broquetas, M., and Volm, J. M. (2013). "The project benefits of Building Information Modelling (BIM)." *International Journal of Project Management*, 31(7), 971-980.

Burns, T. E., and Stalker, G. M. (1961). "The management of innovation." Tavistock, London.

Cao, D., Li, H., Wang, G., and Zhang, W. (2016). "Linking the motivations and practices of design organizations to implement building information modeling in construction projects: Empirical study in China." *Journal of Management in Engineering*, 32(6), 04016013.

Cerovsek, T. (2011). "A review and outlook for a 'Building Information Model'(BIM): A multi-standpoint framework for technological development." *Advanced engineering informatics*, 25(2), 224-244.

Chesbrough, H. W., and Teece, D. J. (1996). "When is virtual virtuous? Organizing for innovation." *Harvard Business Review*, 74(1), 65-74.

Corsaro, D., Cantù, C., and Tunisini, A. (2012). "Actors' Heterogeneity in Innovation Networks." *Industrial Marketing Management*, 41(5), 780-789.

CPIc (2013). "CPIx Pre-Contract Building Information Modelling (BIM) Execution Plan (BEP)." <http://www.cpic.org.uk/wp-content/uploads/2013/06/cpix_pre-contract_bim_execution_plan_bep_v2.0.pdf>. (2017).

Creswell, J. W. (1994). *Research design: Qualitative & quantitative approaches*, Sage Publications., Thousand Oaks, California, USA.

Dainty, A., Leiringer, R., Fernie, S., and Harty, C. (2017). "BIM and the small construction firm: a critical perspective." *Building Research & Information*, 1-14.

de Valence, G. (2010). "Innovation, procurement and construction industry development." *Construction Economics and Building*, 10(4), 50-59.

Dhanaraj, C., and Parkhe, A. (2006). "Orchestrating innovation networks." *Academy of management review*, 31(3), 659-669.

Dorée, A. G. (2004). "Collusion in the Dutch construction industry: An industrial organization perspective." *Building Research and Information*, 32(2), 146-156.

Dossick, C. S., and Neff, G. (2010). "Organizational divisions in BIM-enabled commercial construction." *Journal of construction engineering and management*, 136(4), 459-467.

Dubois, A., and Gadde, L.-E. (2002). "The construction industry as a loosely coupled system: implications for productivity and innovation." *Construction Management & Economics*, 20(7), 621-631.

East, B., and Smith, D. "The United States National Building Information Modeling Standard: The First Decade." *Proc., 33rd CIB W78 Information Technology for Construction Conference (CIB W78 2016)*.

Eastman, C. (1999). *Building Product Models: Computer Environments, Supporting Design and Construction*, CRC Press, Boca Raton, Florida, USA.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2008). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*, John Wiley & Sons Inc., Hoboken, New Jersey, USA.

Eisenhardt, K. M., and Graebner, M. E. (2007). "Theory building from cases: Opportunities and challenges." *Academy of Management Journal*, 50(1), 25-32.

Elmualim, A., and Gilder, J. (2014). "BIM: innovation in design management, influence and challenges of implementation." *Architectural Engineering and Design Management*, 10(3-4), 183-199.

GCCG (2011). "Government Construction Client Group: BIM Working Party Strategy Paper."

Gorard, S., and Taylor, C. (2004). *Combining methods in educational and social research*, McGraw-Hill Education (UK).

Harty, C., and Whyte, J. (2010). "Emerging hybrid practices in construction design work: role of mixed media." *Journal of Construction Engineering and Management*, 136(4), 468-476.

HMG (2015). "Digital Built Britain, Level 3 BIM Strategic Plan." <http://digital-built-britain.com/DigitalBuiltBritainLevel3BuildingInformationModellingStrategicPlan.pdf>.

Kassem, M., Succar, B., and Dawood, N. (2015). "Building Information Modeling: analyzing noteworthy publications of eight countries using a knowledge content taxonomy." *Building Information Modeling:*

Applications and practices in the AEC industry, R. Issa, and S. Olbina, eds., ASCE Press, Reston, VA, USA, 329 - 371.

Klir, G. (2001). *Facets of Systems Science*, Kluwer, New York.

Koolwijk, J. S. J., Oel, C. J., van, Wamelink, H., and Vrijhoef, R. (2018). "Collaboration and Integration in Project-based Supply Chains in the Construction Industry." *Journal of Management in Engineering*, 34(3).

Kvan, T. (2000). "Collaborative design: what is it?" *Automation in construction*, 9(4), 409-415.

Laakso, M., and Kiviniemi, A. (2012). "The IFC standard: A review of history, development, and standardization." *Journal of Information Technology in Construction*, 17, 134-161.

Lee, S., Yu, J., and Jeong, D. (2013). "BIM acceptance model in construction organizations." *Journal of Management in Engineering*, 31(3), 04014048.

Liu, Y., van Nederveen, S., and Hertogh, M. (2016). "Understanding effects of BIM on collaborative design and construction: An empirical study in China." *International Journal of Project Management*.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., and Zacharia, Z. G. (2001). "Defining supply chain management." *Journal of Business logistics*, 22(2), 1-25.

Merriam, S. B. (1998). *Qualitative research and case study application in education*, Jossey-Bass, San Francisco, USA.

Miettinen, R., and Paavola, S. (2014). "Beyond the BIM utopia: Approaches to the development and implementation of building information modeling." *Automation in construction*, 43, 84-91.

Miles, M. B., and Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*, Sage Publications Inc., Thousant Oaks, CA.

Morgan, B. "Organizing for Digitization in firms: A multiple level perspective." *Proc., Proceedings of the 33RD Annual Association of Researchers in Construction Management Conference (ARCOM 2017)*, Association of Researchers in Construction Management.

Morris, P. W. G. (2004). "Project management in the construction industry." *The Wiley guide to managing projects*, P. W. G. Morris, and J. K. Pinto, eds., John Wiley & Sons, Hoboken, NJ, 1350-1367.

Orton, J. D., and Weick, K. E. (1990). "Loosely coupled systems: A reconceptualization." *Academy of management review*, 15(2), 203-223.

Papadonikolaki, E. (2017). "Aligning BIM Adoption Drivers with BIM Implementation in Loosely Coupled Construction Systems." *EPOC 2017-15th Engineering Project Organization Conference with 5th International Megaprojects Workshop*, A. Mahalingham, T. Shealy, and N. Gil, eds.Stanford Sierra Camp, California.

Papadonikolaki, E., Verbraeck, A., and Wamelink, H. (2017). "Formal and informal relations within BIM-enabled supply chain partnerships." *Construction Management and Economics*, 1-22.

Papadonikolaki, E., Vrijhoef, R., and Wamelink, H. (2016). "The interdependences of BIM and supply chain partnering: Empirical explorations." *Architectural Engineering and Design Management*.

Papadonikolaki, E., and Wamelink, H. (2017). "Inter- and intra-organizational conditions for supply chain integration with BIM." *Building Research & Information*, 1-16.

Porwal, A., and Hewage, K. N. (2013). "Building Information Modeling (BIM) partnering framework for public construction projects." *Automation in Construction*, 31(0), 204-214.

Rogers, E. M. (2003). *Diffusion of innovations*, Free Press, New York.

Rogers, E. M., Medina, U. E., Rivera, M. A., and Wiley, C. J. (2005). "Complex adaptive systems and the diffusion of innovations." *The Innovation Journal: The Public Sector Innovation Journal*, 10(3), 1-26.

Sackey, E., Tuuli, M., and Dainty, A. (2014). "Sociotechnical systems approach to BIM implementation in a multidisciplinary construction context." *Journal of management in engineering*, 31(1), A4014005.

Sarantakos, S. (2005). *Social Research*, Palgrave Macmillan, Melbourne.

Shenhar, A. J., and Dvir, D. (2007). *Reinventing project management: the diamond approach to successful growth and innovation*, Harvard Business Review Press.

Shenhar, A. J., Dvir, D., and Shulman, Y. (1995). "A two-dimensional taxonomy of products and innovations." *Journal of Engineering and Technology Management*, 12(3), 175-200.

Son, H., Lee, S., and Kim, C. (2015). "What drives the adoption of building information modeling in design organizations? An empirical investigation of the antecedents affecting architects' behavioral intentions." *Automation in Construction*, 49, Part A, 92-99.

Succar, B., and Kassem, M. (2015). "Macro-BIM adoption: Conceptual structures." *Automation in Construction*, 57, 64-79.

Succar, B., Sher, W., and Williams, A. (2012). "Measuring BIM performance: Five metrics." *Architectural Engineering and Design Management*, 8(2), 120-142.

Taylor, J. E., and Bernstein, P. G. (2009). "Paradigm trajectories of building information modeling practice in project networks." *Journal of Management in Engineering*, 25(2), 69-76.

Taylor, J. E., and Levitt, R. (2007). "Innovation alignment and project network dynamics: An integrative model for change." *Project Management Journal*, 38(3), 22-35.
van Nederveen, G., and Tolman, F. (1992). "Modelling multiple views on buildings." *Automation in Construction*, 1(3), 215-224.
Whyte, J., and Lobo, S. (2010). "Coordination and control in project-based work: digital objects and infrastructures for delivery." *Construction management and economics*, 28(6), 557-567.
Winch, G. M. (2002). *Managing construction projects*, Blackwell Science, Oxford, UK.
Wong, A. K. D., Wong, F. K. W., and Nadeem, A. (2010). "Attributes of building information modelling implementations in various countries." *Architectural Engineering and Design Management*, 6(SPECIAL ISSUE), 288-302.
Yin, R. K. (1984). *Case Study Research: Design and Methods*, SAGE Publications, Beverly Hills, California.

Table 1. Key studies and milestones in the evolution of the concept of Building Information Modeling.

Year	**Milestone**	**Source**
1992	Introduction of term **building information modeling**	(Van Nederveen and Tolman 1992),
1994	International Alliance for Interoperability (IAI) was founded	(Bazjanac and Crawley 1997)
1995	Start of Industry Foundation Classes (IFC) initiatives	(Bazjanac and Crawley 1997)
1999	**Building Product Models** book was published	(Eastman 1999)
2005	IAI was renamed BuildingSMART	Buildingsmart.org
2007	National BIM Standards (NBIMS) in the USA was founded	Nationalbimstandard.org
2008	BIM Handbook was published	(Eastman et al. 2008)
2009	Introduction of **Building information Management** concept	(Becerik-Gerber and Kensek 2009)
2011	The UK BIM strategy was announced	(GCCG 2011)
2015	The **Digital** Built Britain strategic plan was published	(HMG 2015)

Table 2. Indicative list of scope and streams of BIM research.

Relation to innovation	**Perspective**	**Indicative sources**
Adoption (from firms)	micro-level	(Ahn et al. 2015; Akintola et al. 2017; Arayici et al. 2011; Cao et al. 2016; Dainty et al. 2017; Lee et al. 2013; Son et al. 2015)
Implementation (in projects)	meso-level	(Azhar 2011; Bryde et al. 2013; Dossick and Neff 2010; Elmualim and Gilder 2014; Harty and Whyte 2010; Liu et al. 2016; Miettinen and Paavola 2014; Sackey et al. 2014)
Diffusion (across context)	macro-level	Kassem et al. (2015); (Succar and Kassem 2015; Wong et al. 2010)

Table 3. Description of the key features of the three case studies (projects).

	Case A	Case B	Case C
Typology	Multi-functional	Housing (multiple phases)	Housing
Size	Retail, offices, and 255 apartments	83 apartments	44 apartments
Morphology	3 volumes, public square, and parking	1 tower above shopping arcade	2 volumes
Duration	6 years (delays in initiation)	2 years (phase B)	2 years
Completion	April 2016	February 2017	November 2015

Table 4. Description of the interviewees (primary data sources) of the three case studies.

Case A		**Case B**		**Case C**	
Firm (size)	**Function**	**Firm (size)**	**Function**	**Firm (size)**	**Function**
Facility Mgt[1]*	Project Mgr[2]	Contractor*	Project Leader	Client**	Tender Mgr
Contractor*	Site Eng[3]		Site Eng	Contractor**	BIM Director
	BIM Manager	Architect**	Lead Architect		Tender Mgr
	BIM Coordinator		BIM Modeler		BIM Mgr
Architect**	Director	Structural Eng**	Lead Eng		Project Mgr
	BIM Modeler	Mechanical Eng**	Tender Mgr	Architect**	Lead Architect
Structural Eng**	Director		Site Eng		BIM Architect
	BIM Modeler		BIM Modeler	Structural Eng*	Lead Eng
Mechanical Eng*	Project Leader	Subcontractor*	Project Leader	Mechanical Eng*	Lead Eng
Supplier*	Tender Mgr	Supplier**	Director	-	-
	BIM Eng		BIM Modeler	-	-

[1] Management, [2] Manager, [3] Engineer

* Large firm, ** Small- Medium Enterprise (SME)

Table 5. Analysis of the motivations (drivers) for BIM adoption across the case studies.

Case A		**Case B**		**Case C**	
Firm	**BIM motivation**	**Firm**	**BIM motivation**	**Firm**	**BIM motivation**
Facility Mgt[1]	Demand (E[3])	Contractor	*Consistency* (I)	Client	*Quality* (E)
Contractor	*Obligation* (E)	Architect	*Quality* (I)	Contractor	*Business* (I)
Architect	*Interest* (I[4])	Structural Eng	*Future* (I)	Architect	*Quality* (I)
Structural Eng[2]	*Demand* (E)	Mechanical Eng	*Market* (E)	Structural Eng	Demand (E)
Mechanical Eng	*Market* (E)	Subcontractor	*Demand* (E)	Mechanical Eng	Demand (E)
Supplier	Client (E)	Supplier	Quality (I) and *Demand* (E)	-	-

[1] Management, [2] Engineer, [3] External motivation, [4] Internal motivation.

The italicized text in cells denotes the vivo codes.

Table 6. Deployed BIM-based functionalities (artefacts, processes, and structures) among the three case studies.

BIM implementation feature	**Case A**	**Case B**	**Case C**
BIM as a requirement	Yes	No	No
BIM-savvy partners' selection	Yes	No	Yes
BIM-related meetings	Pre-scheduled	On-demand	On-demand
Co-location practices	Predefined	On-demand	Ad-hoc
Use of Common Data Environment	Yes	No (extranet)	No (extranet)
Use of BIM protocol	Project-defined	Project-defined	Firm-based
Model checking tools	Yes	Yes	No
Information exchange file type	Native, IFC[1]	CAD[2]/PDF[3], Native, IFC	CAD/PDF, Native
Deliverable file type(s)	CAD/PDF, IFC (as-built)	CAD/PDF, IFC	CAD/PDF

[1] IFC: Industry Foundation Classes, [2] CAD: Computer-Aided Design, [3] PDF: Portable Document Format