Digital Collaboration in the Wood-based Construction Industry: Deployment of Building Information Modeling

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Abstract

Building Information Modeling (BIM) is intended to promote efficiency in building design and serves as a design space where multiple actors engage in collaborative work. BIM is both a new technology and a new way of working, providing a common environment for all information defining a building, facility, or asset, together with its common parts and activities (Pittard, 2013). This thesis explores the deployment of BIM technology in the Norwegian wood-based building industry and contributes to understanding how BIM can be applied to improve collaborative work in this sector. The dissertation is interdisciplinary in nature, and offers contributions to the fields of information systems (IS), construction informatics (CI), and construction management. It builds on and extends the discourse on BIM deployment in the architecture, engineering, and construction (AEC) industry.

The motivation for undertaking this study is that BIM systems provide the opportunity for increased effectiveness in the process of construction. BIM systems promise to deliver integration across the people, groups, and organizations working in the construction supply chain. The anticipated benefits of BIM include performance gains, increased clarity in information sharing, and a reduction in errors during construction design. BIM systems open up a number of possibilities for the wood-based building industry, such as increasing automation and prefabrication. Higher levels of automation will become possible once project teams have succeeded in collaboratively creating digital BIM models that are sophisticated enough to be turned into machine-readable files.

Despite large investments in BIM systems and computer numerical controlled (CNC) production machinery, the wood-based building industry is in danger of missing out on the potential offered by BIM technology. Through various studies at the group, organizational, inter-organizational, and industry level, prior research has established how many project teams struggle to work with the new BIM technology. The new technology is predominantly used to automate old design processes rather than substantially transform the way in which designs are created and shared. This reflects an untapped potential; consequently, this PhD project was initiated following a request from the wood-based building industry in the Agder region in Southern Norway to explore how BIM deployment could be further improved to maximize the benefits of this new technology.

This investigation focusses on the interactions between people, technology, and organizations in the wood-based building industry. Moreover, this thesis intends to further the understanding of the preconditions or antecedents that would need to be met to enable

BIM-based collaboration in wood-based building projects. The overall objective resulted in the following main research question:

RQ: *How can building information modeling support integrated practice in the wood-based building industry?*

This research question is answered through three sub-questions:

SQ1: What is the current state of BIM adoption for integration in the wood-based building industry?

SQ2: What are the predominant social, environmental, and technical barriers for the adoption of BIM in this industry?

SQ3: What changes will be required with respect to work processes and interaction between the actors in the industry to achieve improved design information sharing through the use of BIM?

These research questions are addressed through three case studies and a focus-group discussion. Altogether, 27 interviews with 31 experienced practitioners were conducted to understand how collaborative BIM-based work unfolds in project situations.

Two cases were typical examples of wood-based construction projects, with one being a more or less industry standard residential project, and the other being an ambitiously designed public library. Selecting these projects allowed for an understanding of the current state of BIM deployment in wood-based building industry projects (SQ1). Moreover, weaknesses in current practice and possible improvements could be identified (SQ2+3). Due to the different nature of the projects, with one being more complex than the other, it was possible to study if BIM deployment was influenced by project complexity. The data obtained in these case studies was analyzed based on two analytical perspectives; namely, configuration analysis and cooperative capabilities. To explore whether the findings were relevant and resembled wider practice in the wood-based building industry, a focus group discussion with a panel of experienced industry experts was undertaken.

The main findings were that while BIM implementation is spreading, collaborative BIM work has shortcomings, as signified by a large number of workarounds and improvisations, resulting in practitioners failing to create sophisticated digital models. Moreover, BIM is currently not perceived to have unconditional, positive implications for all types of projects and its deployment is only prioritized in complex projects. Improvement is possible by increasing levels of cooperative capability, building better inter-organizational information technology (IT) infrastructures, achieving full business process integration, agreeing on shared organizing visions for collaborative work, and by assigning management roles and responsibilities guiding the collaborative design work.

A third case was selected as an “extreme” case of BIM deployment. This involved the construction of a new regional hospital, perceived to be the most advanced case of BIM deployment in Norway to date. While this project was not a case of wood-based construction, it was a good example for innovative BIM deployment where a design team succeeded in integrated, collaborative BIM-based design. This successful case of BIM deployment provided useful ideas on how BIM practice in wood-based construction could be further improved (SQ3). Diffusion of innovations (DOI) theory served as the perspective, revealing factors aiding the design team in succeeding in their BIM work. The factors identified as influential for the successful diffusion of BIM in this project included: (1) appointing change agents; (2) establishing a cloud computing infrastructure facilitating remote and collocated design; (3) creating new roles and responsibilities; (4) designing contracts specifying the desired levels of BIM deployment; (5) employing a systematic approach to IS learning; and (6) involving software developers to help the design team to overcome technical challenges and linking previously unconnected designers in collaborative design work.

The practical contribution of my work highlights how design practice in the wood-based construction industry can be substantially transformed to achieve a more integrated way of working. First, project teams need to agree on a shared organizing vision for working together in BIM. This vision can be built by discussing the desired communication outcomes and the role of BIM in facilitating such communication. Second, new inter-organizational processes need to be crafted based on the desired communication outcomes. Third, a functional IT infrastructure integrating the teams’ design systems for the duration of their collaborative work needs to be put in place. This can take the form of a cloud-based BIM server infrastructure allowing for distributed design. Software developers need to be involved to ensure that all of the previously unconnected design team members are tied into the shared infrastructure. Fourth, BIM champions are required to create stable information flow from the early design stage to the code generator creating the machine-readable files. Fifth, the design team needs to possess cooperative capabilities that are sophisticated enough to enable them to collaborate based on BIM and CNC. This can be achieved by adopting a structured approach to IS learning at the project level. Sixth, design teams need to conduct a cost–benefit analysis for BIM-based work by taking project complexity into account. Moreover, a client’s commitment is of the utmost importance for successful BIM diffusion. Lastly, to streamline the information flow toward those designers creating CNC data, all team members need to be included early on, decision making needs to be frontloaded, and the design needs to be “frozen” before construction work commences.

The theoretical contributions of my work include an extension of the application of configuration analysis to the field of construction management. Moreover, it has been shown that this theoretical perspective extends the understanding of strategic and structural arrangements for BIM. By applying a cooperative capability lens with which to compare the collaborative performance in two construction projects that differ in complexity, the relationship between project complexity and collaborative work becomes explicit. Further, I extended the application of DOI theory in the construction informatics literature by exploring project-level diffusion factors in a case involving successful BIM diffusion. Lastly, I advanced a new conceptual model derived from the patterns observed in collaborative BIM-based work in the case projects. At the core of this model is an actor’s “freedom of enactment,” which is the condition where an actor is free to deploy BIM systems in a project situation. This model conceptualizes how the characteristics of project-based work influence digital collaborative work. Studying recent developments in BIM technology and their impact on industrial practice contributes to highlighting the role of IS as an important reference discipline in the domain of building construction. Moreover, my research contributes to better understand BIM’s role in collaboration, which is a topic area receiving little attention in mainstream IS journals. Further, my work contributes to drawing the attention of the IS community to BIM as an interesting topic area for IS research.

Based on the literature review and the findings of this research, several areas in need of further research could be identified. Examples of interesting research questions include what the value is of cloud computing and virtual teamwork for construction design. How can the content produced in BIM design be managed to be useful for facilities management? How can BIM technology be further improved to better serve its purpose as a collaborative system?

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Being part of the information systems group at the University of Agder (UiA) while pursuing my PhD degree was, quite simply, a great experience. When I arrived in Kristiansand in 2011, I still had, as my advisor put it, my “industry goggles” on after working for six years in construction management. During the past three years, I have gotten a brand new pair of “research goggles.” In other words, I have learned the handcraft of being a researcher. My mentor throughout this process was Professor Bjørn Erik Munkvold, and I owe him a debt of gratitude for his constant support, guidance, and professionalism. Bjørn Erik made me feel confident throughout the research process, and he taught me many “tricks of the trade,” and what it means to be a researcher.

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List of Abbreviations

AEC	architecture, engineering, and construction
BIM	building information modeling
CAD	computer aided design
CAM	computer aided manufacturing
CI	construction informatics
CNC	computer numerical control
IS	information systems
IT	information technology
IOIS	inter-organizational information system
IFC	industry foundation class
IPD	integrated project delivery
RBV	resource based view

1 Introduction

Statistics show that all construction information needs to be re-created and/or re-entered four to eight times throughout the life-cycle of a project (Davis, 2007). This represents a waste of time, human capital, and information technology (IT) capability, which could be prevented by improved collaborative work. Realizing the need for change, many government and private sector organizations in architecture, engineering, and construction (AEC) seek to improve information sharing and collaborative work in their projects. The US National Institute of Standards and Technology published a report entitled “Cost Analysis of Inadequate Interoperability in the US Capital Facilities Industry” (Gallaher, O'Connor, Dettbarn, & Gilday, 2004), in which they stated that by improving information sharing and process continuity, USD 15.8 billion would be saved per year in the US capital facilities industry alone.

One possible way to achieve higher levels of integration in construction projects is to increase the use of information systems (IS) for collaborative work (Xue, Shen, Fan, Li, & Fan, 2012). There are three main application areas for collaborative IT in AEC: (1) collaborative design, (2) collaborative construction management, and (3) integrated, inter-organizational management of IS (ibid.). This thesis studies IS spanning all three application areas; namely, building information modeling (BIM). A BIM system is defined as “a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” (NIBS, 2007).

This dissertation emphasizes the application of BIM technology and studies the interaction between people, organizations, and technology. It draws upon multiple case studies to derive empirical insight as well as to expand the conceptual knowledge on BIM-supported collaborative work in building construction. The industrial environment providing the contextual space for this study is the Norwegian wood-based building industry. In this part of the AEC industry, new 3D BIM systems increasingly replace older 2D computer-aided design (CAD) systems.

The primary motivation for conducting this research is that BIM systems are important. First, they promise to deliver integration across the individuals, groups, and organizations working in the construction supply chain (Shen et al., 2010). Second, they promise to enhance the clarity in architectural expression (Yan, Culp, & Graf, 2011).

Last, they serve as catalysts for innovation in the construction industry, which is needed to modernize this sector of the economy (Boland, Lyytinen, & Yoo, 2007; Egan, 1998).

Another motivation for undertaking this research is that the use of BIM for collaboration and integration is challenging. So far, only few, highly IT literate, and leading construction corporations enjoy the benefits of BIM technology, whereas those working on the periphery of the digital innovation networks (e.g. small architectural offices, contractors, fabricators, and suppliers) are frequently excluded from innovative practices (Leeuwis, Prins, & Pastoors, 2013; Yoo et al., 2010). This thesis seeks to contribute to addressing this problem by developing an understanding of the antecedents of collaborative BIM work that would need to be met before the benefits of BIM technology come within reach. Last, the exciting potential to contribute to transforming a major industry such as building construction provides a strong rationale for undertaking research in this area.

1.1 The Regional Wood-based Building Industry

The industrial environment providing the context for this research is the wood-based building industry in the Agder region of Norway. This doctoral project has been established based on an initiative from this industry. The funding for this work was provided by Vest-Agder County Municipality and the Competence Development Fund of Southern Norway. The doctoral project was initiated as a means to explore how next-generation technology could aid in optimizing processes in the local wood-based building industry (Torkelsen, 2010).

Timber is a widely used building material in Norway and a logical material choice for Norwegians, as their country’s surface area is covered by 37% of forest (Khemlani, 2005). Several remarkable examples of cutting-edge wood construction can be found in Norway, including Oslo Airport (1994–1998) and the Hamar Olympic Hall “the Viking ship” (1994) (ibid.). Since the 1990s, several concerted efforts across both the private and public sectors have been made to improve the performance of the Norwegian wood-based building industry (Hampson, Kraatz, Sanchez, & Herron, 2013). Examples of such initiatives include the Agder Wood Initiative (www.agderwood.no) and the national research program Treprogrammet. Both focus on how the wood-based building industry can improve the sustainability of its products.

In the Agder region of Norway, timber has a strong position in comparison with other materials when it comes to the construction of detached houses and other small buildings, and timber has become a popular material for larger buildings, and for buildings spanning several floors. Examples of this trend include ambitiously designed structures such as the Kristiansand concert hall “Kilden” (2012) or the new public library in Vennesla (2011). The wood-based building industry is an important actor in creating the region’s building stock.

Off-site fabrication and pre-assembly have a long tradition in Norwegian wood-based construction (Schmidt, 2009). By moving much of the work into tidy, dry, and controlled factory environments, contractors escape the often-harsh Norwegian weather conditions. Off-site production significantly improves the quality of the delivered products. Further, it allows contractors to streamline their operations by reducing wasteful activities and eliminating inefficiencies. Many contractors in Agder have invested heavily in prefabrication and have put plant, equipment, and buildings in place for this purpose, and more recently, they have installed computer numerical controlled (CNC) fabrication machinery and BIM systems. The concept of CNC involves automated milling tools such as drills and saws being controlled by programmed commands describing a series of movements and operations.

The purpose of introducing BIM and CNC is to automate the production of non-standard architectural elements through a “mass-customization” approach. BIM is used to design the parametric detail and CNC machining units produce the wooden elements with unique parameters. The core idea is to take an architect’s data and to produce the elements *directly* without costly redesign. This automated production process is often referred to as “file to factory” or as a “digital fabrication environment”, and is seen as a key driver in achieving higher levels of industrialization and prefabrication in wood-based construction (Khemlani, 2005; Scheurer, 2010; Schmidt, 2009).

BIM technology and CNC machining units are still underutilized. They are mainly used to speed up the production of simple building components such as trusses or timber frames instead of producing more advanced architectural components (Larsen, 2008; Scheurer, 2010). Thus, the wood-based building industry is missing out on the unique opportunity to join design and construction by combining BIM and CNC (Sass, 2007). Digital fabrication environments based on BIM and CNC technology will only become a reality when all design team members, ranging from architects and engineers to fabricators, intensify BIM-based collaboration. Given that Agder’s wood-based building industry has witnessed heavy investments in automation, this part of the AEC industry provides us with a compelling context for this study.

1.2 Problem Statement

How can higher levels of collaboration and integration in the design and construction of wood-based facilities be achieved through the use of BIM? According to Succar (2009), integrated, collaborative BIM-based work is only achieved when 1) organizations succeed in creating joint, semantically rich virtual models by using model server architecture; 2) the information content of the virtual models is sophisticated enough to support advanced analytical operations (e.g. structural analysis, airflow simulations, or fire-spread simulations); and 3) the collaborative work begins to spiral iteratively between the parties involved in the design and construction of a facility.

Achieving high levels of integration in the context of building construction is anything but easy (Linderoth, Jacobsson, & Rowlinson, 2011). Several characteristics of the AEC industry hinder integrated IT-based work, such as its production environment, procurement strategies, and the way in which the construction work is organized (ibid.). Yet, there is a lack of studies investigating how collaborative IT can be effectively implemented in construction projects (Xue et al., 2012). Shen et al. (2010) therefore highlight the importance of developing methodologies for IT-based collaborative work in construction.

Any IT implementation process is more than a software purchase; it disrupts the usual way of getting things done (Battilana & Casciaro, 2013). Implementing collaborative IT such as BIM requires changing work processes, organizational roles, and information infrastructure across several organizations (Gal, Lyytinen, & Yoo, 2008). Further, the contextual space in which the implementation takes place matters, as the degree to which the system is deployed depends on the actors' interests, competencies, and characteristics (Chiasson & Davidson, 2005; de Vreede, Briggs, & Massey, 2009). Pries-Heje and Baskerville (2010) suggest that successful organizational change requires a strategy that takes into account the "essential attributes of the organizational setting" (p. 274). Thus, in construction projects where "work has vast complexity and variety" (ibid., p. 276), a different IT implementation strategy may be needed than in "relatively stable surroundings" (p. 276) where the work is more or less industry standard.

Despite the heavy investments in automation and BIM technology, the wood-based building industry is still missing out on many of the benefits that the technology has to offer (Larsen, 2008; Scheurer, 2010). This thesis focuses on understanding the preconditions or "antecedents" that would need to be met in order to enable BIM-based collaborative design. Providing this conceptual and empirical knowledge would aid the wood-based building industry in coming closer to realizing their vision of digital fabrication environments. The main research question is formulated as follows:

How can Building Information Modeling support integrated practice in the wood-based building industry?

To answer this research question, the thesis explores a number of sub-questions representing various aspects of the phenomenon under study:

SQ1: What is the current state of BIM adoption for integration in the wood-based building industry?

SQ2: What are the predominant social, environmental, and technical barriers for the adoption of BIM in this industry?

SQ3: What changes will be required with respect to work processes and interaction between the actors in the industry to achieve improved design information sharing through the use of BIM?

To answer the research questions, three case studies on collaborative BIM use in Norwegian construction projects were undertaken, involving three types of building projects with different complexity: a residential building complex, a public library, and the construction of a new regional hospital. The first two cases represent examples of BIM-based work in wood-based building projects. The residential project can be seen as a more or less industry standard type of project, whereas the library project was complex and ambitiously designed. Analyzing two projects of differing complexity offered the opportunity to gain an understanding of how collaborative design based on BIM is influenced by the complexity of a building project. The hospital case was chosen because it was a national "leading example" of BIM use in the general AEC industry. In addition to the case studies, a focus group discussion was held with industry experts, all of whom had considerable experience in collaborative BIM-based design.

1.3 Overview of the Theoretical Perspectives

The thesis uses a combination of analytical perspectives, which all offer explanations that are useful in understanding digital collaboration in construction projects (Okhuysen & Bonardi, 2011). The motivation for doing so is to develop a robust explanation of the empirical problem that is being addressed. The core theoretical perspectives applied in this thesis are configuration analysis (Lyytinen &

Damsgaard, 2011), cooperative capability analysis (Blomqvist & Levy, 2006; Tyler, 2001), and diffusion of innovations (DOI) theory (Rogers, 2010).

Configuration analysis is an analytical perspective developed for the study of inter-organizational IS (IOIS) (Lyytinen & Damsgaard, 2011). Configuration analysis has its origin in organizational theory where organizations and markets are defined as interconnected structures (Williamson, 1979). This perspective enables the study of the alignment among a set of organizations that are interrelated through their IS. This perspective is useful for analyzing, explaining, and understanding BIM-enabled interaction in a construction project.

Cooperative capabilities. How well firms use the advantage of technologically based innovations is shaped by organizational competencies that enable firms to exploit the results stemming from these assets (Tyler, 2001). This line of thinking has its origin in the resource-based theory of the firm where the resources at a firm's disposal can be turned into a competitive advantage (Wernerfelt, 1984). Tyler (2001) argues that a firm would need cooperative and technological capabilities "consisting of information processing, communication, knowledge transfer and control, the management of intra- and inter-unit coordination, trustworthiness or the ability to engender trust, and negotiation skills" to exploit inter-organizational information and communication technology (ICT) (Tyler, 2001, p. 2). Studying the capabilities displayed by professionals in a construction project is useful for understanding the degree of sophistication achieved in BIM-based work.

DOI theory is concerned with how and why an innovation becomes diffused in a social system (Rogers, 2003). Its strength is that it allows for an understanding of the antecedents of technology adoption (Robey, Im, & Wareham, 2008). Classic diffusion research views innovation diffusion as a linear process, but further development of the theory offers new insights by accounting for "local, complex, networked, and learning intensive features of technology, [and] the critical role of market making and institutional factors shaping the diffusion arena" (Lyytinen & Damsgaard, 2001, p. 14). DOI theory is widely used for both the study of technologies having an "intra-organizational locus of impact" (ibid., p. 20) and for studies of inter-organizational systems adoption (Robey et al., 2008). Studying the diffusion of complex, networked technologies such as BIM requires researchers to go "beyond what has been suggested in classical DOI theory by trading generalizability and simplicity against accuracy" (ibid., p. 14). Taking the aforementioned into account, DOI serves well to identify the inter-organizational factors driving the diffusion of BIM at the project level.

1.4 Results

The results of this research have been presented in six articles published in international journals and international conference proceedings. All of the articles contribute empirical or theoretical insights into the main research question of this thesis. The papers and their relation to the research sub-questions are listed in Table 1-1. As shown in the table, the papers contribute to different aspects of the phenomenon under study. The grey scale indicates the degree to which each paper addresses a particular research question. By drawing upon the extant literature (paper 1), by providing and comparing two cases from the wood-based building industry (papers 2–4), through a focus-group discussion with a panel of industry experts (paper 5), and a case from advanced BIM practice (paper 6), this thesis addresses the main research question, and maps a way forward for integrated, BIM-based design in the wood-based building industry. Further details on how the individual papers contribute to answering the research questions can be found in Chapter 4, and the six papers are included in Appendix C.

Table 1-1 *Relationship between Article Focus and the Research Question: Dark Gray Indicates a Full Match, Gray Indicates a Partial Match, and White Is No Match*

Paper	**SQ1**	**SQ2**	**SQ3**
1) A Research Review on Building Information Modeling in Construction: An Area Ripe for IS Research			
2) Unorchestrated Symphony: The Case of Inter-organizational Collaboration in Digital Construction Design			
3) How Is Building Information Modeling Influenced by Project Complexity? A Cross-case Analysis of e-Collaboration Performance in Building Construction			
4) Actors' Freedom of Enactment in a Loosely Coupled System: The Use of Building Information Modeling in Construction Projects			
5) Improving Inter-organizational Design Practice in the Wood-based Building Industry			
6) Succeeding with Building Information Modeling: A Case Study of BIM Diffusion in a Healthcare Construction Project			

1.5 Structure of the Thesis

This introductory chapter has presented the motivation for this work, placed it in its context, presented the problem, and justified the focused research questions. Chapter 2 provides the background literature and introduces the theoretical perspectives chosen as a basis for the research. Chapter 3 introduces the research strategy and the chosen methodologies. Chapter 4 presents an overview of the results, with a brief summary of each publication. Chapter 5 presents the contributions of my work. Chapter 6 concludes the thesis by presenting my answers to the research questions, the limitations of my work, and the implications for further research. Last, the thesis includes three appendixes containing a sample interview guide (Appendix A), an example of the coding work undertaken (Appendix B), and the six publications forming the basis of the thesis (Appendix C).

2 Related Research and Theoretical Perspectives

This chapter introduces the BIM artifact, provides an overview of recent developments in the BIM deployment literature, and introduces the main theoretical perspectives applied in this literature. Further, the theories used in the thesis are introduced and the chapter concludes by presenting how these perspectives complement each other in providing an understanding of the empirical phenomenon under study. The main theoretical perspectives used in this thesis are configuration analysis (Lyytinen & Damsgaard, 2011), cooperative capabilities (Tyler, 2001), and diffusion of innovation theory (Rogers, 2010). Combining theoretical perspectives is useful for developing robust explanations and for strengthening the plausibility of the research findings (Okhuysen & Bonardi, 2011; Robey & Boudreau, 1999). The scope, boundaries, and explanations provided by each perspective are presented (Gregor, 2006). Moreover, arguments for why the chosen perspectives were considered as a good fit in supporting the analysis in this thesis are offered.

2.1 Building Information Modeling: The Artifact Explained

BIM is a "modeling technology and associated set of processes to produce, communicate, and analyze building models" (Eastman, Teicholz, Sacks, & Liston, 2011, p. 16). Building models consist of "components that are represented as digital representations (objects) that carry computable graphic and data attributes that identify them to software applications, as well as parametric rules that allow them to be manipulated in an intelligent fashion" (ibid., p. 16). These building components include data that describe how they behave, which are needed for analysis and work processes.

The crucial difference between BIM and earlier non object based 3D CAD solutions is the concept of parametric objects. Parametric objects consist of geometric definitions and associated data rules (Eastman et al., 2011). Parametric objects will automatically modify associated geometries when inserted into a building model or when they are changed: "Doors will fit automatically into a wall [and] a light switch will automatically locate next to the proper side of the door" (ibid., p. 18). Individual parametric objects are linked to a relational database to receive, broadcast, or export sets of attributes (ibid.). Thus, BIM models are far more "intelligent" than the older 2D and 3D CAD technologies.

The conceptual underpinnings of BIM systems were established in the earliest days of computing. Engelbart (2001) argued in his 1962 paper "Augmenting Human

Intellect” that future architects would be able to join (1) object-based design, (2) relational databases, and (3) parametric manipulation. However, it took roughly half a century until his vision became a reality.

(1) *Object-based design* became possible with the emergence of solid geometry modeling programs. In 1963, the first computational solid modeling programs came into being. This technology has been developed by the MIT Lincoln Laboratory as part of the graphical interfaces required for the semi-automatic ground environment (SAGE) air-defense system (Grometstein, 2011). This system was “pioneering in its complexity and required numerous inventions, including digital computers, magnetic-core memory, large-scale computer programs, modems, and graphical interfaces” (ibid., p. 5). Solid modeling technology makes it possible to describe a geometrical object in 3D space fully. Modern solutions allow for photorealistic graphical rendering of the “solid” objects and for viewing them from any possible angle.

(2) *Relational databases* for building products came into being in 1979. The database called the building description system (BDS) was developed by Charles “Chuck” Eastman in 1979 at Carnegie-Mellon. Fusing both “solid” object modeling technology and relational databases for building products led to the development of early BIM solutions. Perhaps the earliest BIM solution that ran on personal computers was Radar CH, a predecessor of what is known today as ArchiCAD®, running on Apple’s Lisa operation system in 1984. Naturally, specifying sets of properties for building products in digital libraries is far from easy and is literally “Sisyphus work.” To keep abreast of the latest product developments in the building supply industry and to add new product data to a relational database is a continuously ongoing effort. Today, industry-led organizations such as buildingSMART© work continuously on embedding digital templates for new building products into relational databases.

(3) *Sophisticated software for parametric manipulation* became available for the building industry in 2000. A developer called Charles River Software built BIM software called Revit©, based on novel “parametric change engines,” which increased the intelligence of the objects by enabling their automated modification. This can be seen as a quantum leap in the development of BIM systems as they became far easier to handle. In 2002, Autodesk™ bought Charles River Software and began to promote Revit© software and BIM technology in general. This triggered what is today an industry-wide diffusion of BIM (McGraw-Hill, 2012). BIM is increasingly replacing other CAD technologies, including 2D and 3D CAD. Examples for BIM systems

allowing for the design of complex architectural shapes include Bentleys' generative components system (2003) or Gehry Technologies' BIM system (2006).

Another characteristic that differentiates BIM from other CAD tools is that it supports project team collaboration. When linked properly, BIM systems allow for tighter and easier integration among the different designers involved in a project (Eastman et al., 2011). For example, when the architectural model is changed, it will generate changes in the electrical systems model and vice versa (ibid.). After an increasing diffusion of BIM technology, its collaborative use is the next big milestone to be achieved in BIM's evolution. In Norway, large state clients are demanding collaborative BIM work from the beginning of 2016 in all major public developments. Figure 2-1 provides an overview of the significant milestones in BIM's history.

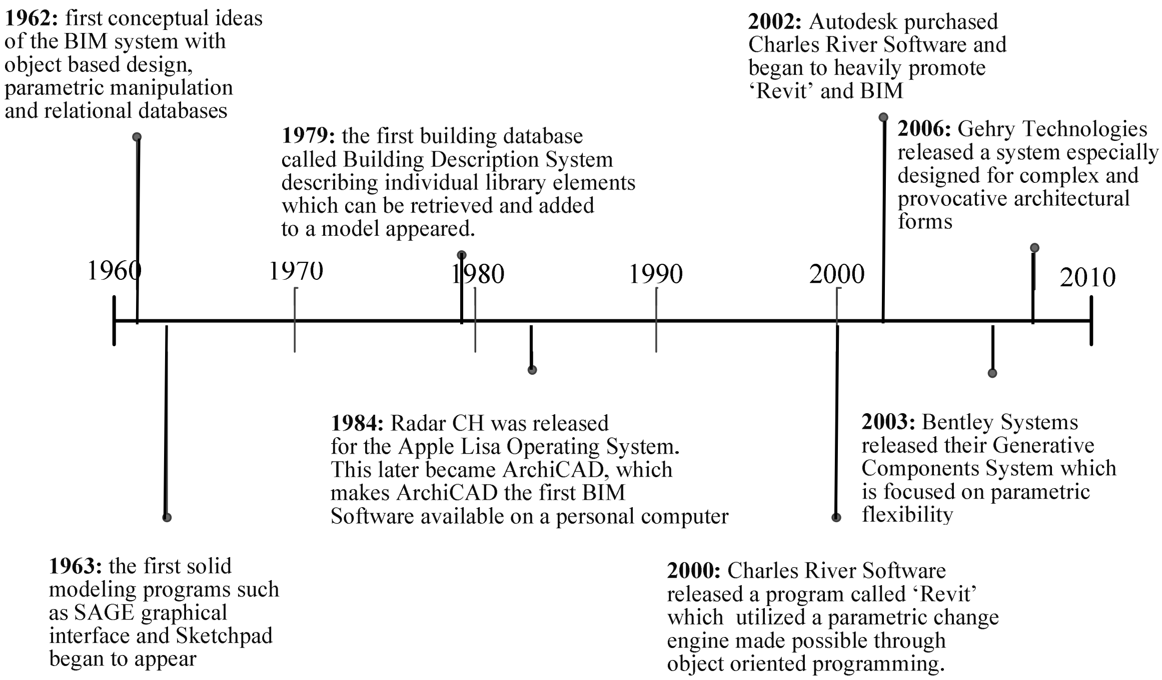


Figure 2-1. Evolution of BIM technology 1960–2010.

Several "wood-specific" 3D CAD and BIM design solutions are commercially available. These solutions all allow for producers of wooden components to send production data that are created based on modeling technology (3D CAD and BIM) directly to CNC machining centers or assembly lines. Examples of such systems include Cadwork®Wood and HSB®Cad, which are, in essence, 3D CAD/computer-aided manufacturing (CAM) solutions specifically designed for the production of wooden architectural components. Naturally, for manufacturers to maximize the utility of their advanced manufacturing systems, sophisticated digital models are required. These models need to be created through the close collaboration of all of the design team members.

2.2 Deploying Building Information Modeling

Before embarking on the theoretical discussion, it is important to provide an overview of current developments in the literature regarding BIM and its application in the construction industry. For this, I will draw upon some of the results from the review article developed as part of this thesis, titled “A Research Review on Building Information Modeling in Construction: An Area Ripe for IS Research” (see Section 4.1 and Appendix C). Based on a systematic review of 264 journal publications on BIM, the article provides an overview of the nature and scope of research that has been conducted in this area. To account for recent developments, some articles published after the review’s cut-off date (December 2011) will be presented in this chapter as well. The review examined articles that were presented in journals of varying academic disciplines. The most active discourse in this topic area takes place in engineering journals and only a few articles in IS journals could be identified. This reflects a largely untapped potential for IS researchers to contribute to this discussion.

Several limitations in this body of literature representing research avenues that are worth pursuing in further work have been identified. What follows is a presentation of the ongoing research on BIM deployment in groups, organizations, and the AEC industry. Deployment is defined in this thesis as comprising all of the activities ranging from making an IT solution available for use to the operation phases after adoption. Before advanced, full-scale use of an inter-organizational system is achieved, several preconditions need to be met (Munkvold, 2008). A series of actions and decisions ranging from the establishment of the IT infrastructure to agreeing on what type of systems should be deployed are needed before the new system can be used to its fullest potential (ibid.).

The deployment of digital design and communication technologies in AEC has triggered interest in several research disciplines including IS (Berente, Baxter, & Lyytinen, 2010; Boland et al., 2007; Gal et al., 2008) and its sub-disciplines of computer-supported cooperative work (CSCW) and participatory design (PD) (Schmidt & Wagner, 2004; Wagner, Stuedahl, & Bratteteig, 2010). For example in IS research, attention is placed on topics such as whether the use of modeling technology leads to innovation or a transformation of organizational processes (Ahmad & Sein, 2008; Boland et al., 2007). CSCW and PD provide for close observations of organizational work and human behavior in digital design (Christensen, 2008; Schmidt & Wagner, 2004; Tory et al., 2008).

However, most of the research activity on BIM deployment topics takes place in construction informatics, construction management, and other engineering disciplines. CI is a research discipline that seeks to bridge the gap between computer science and construction (Björk, 1999). According to Turk (2000), CI is a discipline in its own right, with chairs and departments established in universities around the world. The domain of interest in CI comprises IT-oriented topics spanning several AEC disciplines, such as integration, product modeling, construction documentation, engineering design cycles, and concurrent engineering.

Industry-, project-, and organization-wide BIM deployment has gained much research attention. Researchers study different dimensions and topics, such as the barriers to and the benefits of BIM adoption (Aranda-Mena, Crawford, Chevez, & Froese, 2009), industry-wide BIM adoption rates (Gu & London, 2010), and organizational adoption maturity (Succar, Sher, & Williams, 2012). Moreover, some work is devoted to developing strategies for BIM deployment. What unites this work is a common agreement that the construction industry faces large structural difficulties that hinder BIM deployment.

Industrial context is important, and its features can shape the adoption and deployment of ICT (Chiasson & Davidson, 2005). Features of the AEC industry negatively influencing the deployment of BIM include its fragmented nature, the slow development of common data-exchange practices, and the lack of knowledge about the possibilities of ICT (Dubois & Gadde, 2002; Howard & Björk, 2008; Linderoth et al., 2011). In construction projects, multiple, differentiated tasks executed by various organizations need to be coordinated. Governance structures, financial control, and decision making in construction projects are loosely coupled and decentralized (Dubois & Gadde, 2002; Linderoth et al., 2011).

A decentralized governance structure may cause a lack of commitment and investment in inter-organizational ICT. As Linderoth and colleagues (2011) put it: “Nobody feels responsible for long term investments in ICT facilitating what is best for the project” (p. 10). Moreover, construction projects are tendered based on a competitive “lowest price” policy, leading to the danger that actors may hesitate in adopting costly inter-organizational systems such as BIM. What amplifies the hesitation to invest in BIM is the temporary nature of construction projects. Newly adopted systems may become obsolete for the next project because there will be a “new constellation of actors with (maybe) new versions of ICT applications” (ibid., p. 10). Product vendors add to the aforementioned issue by releasing a multitude of applications while common data-exchange standards are still emerging. Last, buildings are immobile products and it has been historically troublesome to provide remotely located construction sites with the bandwidth and infrastructure required for sophisticated ICT-based work (ibid.).

The aforementioned market and production conditions lead firms to look for short-term gains and immediate benefits from BIM deployment (Jacobsson & Linderoth, 2010). Studies based on the technology acceptance model (TAM) (Davis, Bagozzi, & Warshaw, 1989) report that while many executives remain skeptical toward deploying BIM, it is generally considered a useful tool for improving a building's quality, its timely completion, and for reducing the working hours that are required to create the building (Kubicki, Guerriero, & Johannsen, 2009; Suermann & Issa, 2009). Practitioners judge the usefulness of BIM systems on a project-by-project basis. If BIM is not perceived as useful for improving ongoing work, it will be regarded as "an obstructive element for effective operations and project delivery" (Wikforss & Löfgren, 2007, p. 344). Before interfering with ongoing operations in a project by deploying BIM, the benefits of doing so need to be clearly evident (ibid.). This indicates that perceptions of BIM's usefulness depend on the type and complexity of a construction project. How project complexity relates to BIM deployment is a topic that is focused on in this doctoral project.

As a result, BIM is mainly deployed as a tool to control, automatize, and rationalize existing intra-organizational processes (Linderoth et al., 2011). There is a wealth of studies on BIM deployment guided by automation and rationalization considerations. This work discusses how BIM could be used to cut costs in operations by speeding up the production of drawings, improving jobsite management (Perkinson, Bayraktar, & Ahmad, 2010), improving collision control (Huang, Kong, Guo, Baldwin & Li, 2007), and by supporting cost (Shen & Issa, 2010) and time estimations (Hartmann, Gao, & Fischer, 2008). Thus, many firms continue to work in "siloed" environments instead of encouraging a more collaborative culture by deploying BIM systems to facilitate inter-organizational digital collaboration (Neff, Fiore-Silfvast, & Dossick, 2010).

Several studies focus on how BIM technology can be further diffused in the AEC industry. Examples of this work are the studies by Peansupap and Walker (2005, 2006a, 2006b, 2009). In this work, a technological diffusion approach (Cooper & Zmud, 1990; Fichman, 2000; Rogers, 2010) is applied to develop an understanding of the factors that are relevant for the diffusion of BIM. A broad range of individual, environmental, managerial, and technical factors that are considered as important for triggering BIM deployment have been identified. These factors include designers' personal interest in and willingness to learn technology (Peansupap & Walker, 2009), and the presence of an open discussion environment, colleague help, and organizational support (Peansupap & Walker, 2005). In addition, the extent to which BIM is deployed in projects depends upon organizational maturity and capabilities (Succar, Sher, & Williams, 2012). Considering that BIM is a network-based solution linked to external databases sharing object-based models with at least two disciplines, the competencies of each actor involved will determine the extent to which the system can be used to its full potential.

Once BIM has been taken into use, there is a tendency for construction organizations to "rush headlong into it [BIM-based work] without making the proper organizational changes" (Oakley, 2012). As a result, scholars find that BIM practice is often "static," with designers independently creating disciplinary models that are then exchanged in meetings (Dossick & Neff, 2011). To build more effective work practices and routines, the traditional 2D-based pattern of inter-organizational relationships would need to be disrupted (Dossick & Neff, 2013; Gal et al., 2008; Neff et al., 2010). New processes need to be designed, built, tested, and incrementally improved over a number of projects to become effective (Whyte & Lobo, 2010). Enabling higher levels of integration with collaborative work spiraling iteratively between the involved parties can therefore become a lengthy process (Munkvold, 2008).

To explain the phenomena emerging when BIM is used as a collaborative design system, theories such as boundary objects (Star & Griesemer, 1989) and actor-network theory (ANT) (Latour, 1987) have been applied. Conceptualizing BIM deployment as a creation of actor networks aids in understanding the mechanisms constraining and facilitating BIM-based networks (Linderoth, 2010). This understanding is important, as each time a new project is started up, a new actor network needs to be created (ibid.). Despite their importance, only a few ANT studies on BIM as a technological artifact could be identified in the literature. A potential explanation for this could be the complexity associated with ANT studies, where a veritable mass of detail would need to be presented in research articles (Walsham, 1997). In addition, ANT is designed to capture the translation process toward creating networks over a sustained period of time, which is seldom available in construction projects.

Boundary object theory has been applied to study mutual organizational practices in large construction projects (Gal et al., 2008; Neff et al., 2010). This work conceptualizes BIM technology as boundary objects, used at the shared interface among organizations. By doing so, in conjunction with looking into information infrastructure and organizational identities, the researchers portray how organizational roles and identities are influenced by the way in which BIM technology is deployed (Gal et al., 2008). While the boundary objects perspective has the strength to explain socio-technical phenomena, it has been argued that it does not provide a sharp enough lens through which to understand complex networked technology such as BIM in projects that are highly complex and non-routine with “disorderly” processes (Lee, 2007). The work by Gal and colleagues (2008) illustrated that boundary objects would need to be complemented by additional concepts in order to become useful for the study of BIM.

The potential benefits and drawbacks of BIM deployment for organizations are also debated in the literature. The frequently mentioned benefits of inter-organizational BIM-based collaboration include its positive impact on corporate innovativeness (Boland et al., 2007; Rankin & Luther, 2006), a reduction in unnecessary rework (Shen et al., 2010), and the improvement of clarity in terms of architectural expression (Yan et al., 2011). The high investments associated with IT/IS deployments (Ku & Taiebat, 2011), the lack of skilled personnel (ibid.), and the fact that established ways of getting things done are disrupted (Gal et al., 2008) are among the frequently mentioned drawbacks. Despite increasing BIM uptake (McGraw-Hill, 2012), many of the crucial advantages the technology has to offer remain unexplored in wider practice (Ahmad & Sein, 2008; Ahmad, Sein, & Panthi, 2010; Isikdag, Underwood, Kuruoglu, Goulding, & Acikalin, 2009; Leeuwis et al., 2013). Many attempts at establishing digital BIM-based collaboration fail (Neff et al., 2010). In addition, even in the “world-leading” BIM deployments, opportunities for virtual analysis and other critical areas remain unexplored (McCuen, Suermann, & Krogulecki, 2011).

How can building information modeling deployment research be complemented? There is an emerging research focus on how BIM deployment affects people's everyday interactions and communication (Baxter, 2008). This work is needed, as studying the linkage between the technical and social aspects would provide a greater and more general understanding of BIM-based communication (ibid.). However, this perspective is just emerging, and only a few articles could be found in the literature (Gal et al., 2008; Linderoth, 2010). Considering that BIM systems are intended to serve as design spaces to facilitate the collaborative dialogue among the parties in a construction project, this scarcity of studies is unexpected. Several researchers have argued that BIM’s role in collaboration deserves more research attention (Baxter, 2008; Wikifors & Löfgren, 2007). This work could be informed by the inter-organizational information systems literature (Robey et al., 2008).

Researchers in inter-organizational systems have developed a variety of theoretical arguments to explain the formation of IOIS (Robey et al., 2008). They have used theories such as transaction-cost economics (Williamson, 1979), DOI (Rogers, 2010), boundary objects (Star & Griesemer, 1989), or the resource-based view (RBV) of the firm (Wernerfelt, 1984) as starting points for developing their arguments. To provide a faithful account of IOIS deployment, they include additional findings "regarding network externalities and the social context surrounding IOIS adoptions" (Robey et al., 2008, p. 512). An example of a theory that has been customized for the study of IOIS deployment is the configuration analysis approach developed by Lyytinen and Damsgaard (2011), to be presented in the next section.

Despite an increasing uptake of BIM technology, the current focus of researchers and practitioners on the optimization of existing processes rather than redesign reflects an untapped potential, similar to that which has been pointed out in the early business process reengineering literature (Hammer, 1990). The literature review conducted thus supports the argument that BIM's "transformational capability" to revolutionize and change the way in which AEC organizations do business has yet to be understood (Ahmad & Sein, 2008, Ahmad et al., 2010; Isikdag et al., 2009). There is a need for more research identifying how current practice can be substantially transformed. As Anderson and Bourne (2004) put it: "We believe that this situation provides a real opportunity for any construction firm bold enough to radically innovate" (p. 14). This type of work would aid practitioners in moving on from operating as a group of stand-alone organizations toward integrating their supply chain.

BIM deployment is influenced by the features of the industry, projects, and people involved (Linderoth et al., 2011). These pieces of the puzzle do not necessarily fit well together, and in order to succeed with BIM deployment, "mutual adaptation between technology and its context acknowledging the crucial role of the people involved" will be required (Wikforss & Löfgren, 2007, p. 344). Especially the loosely coupled, "siloed" governance structure applied in many projects produces a challenging environment for the deployment of collaborative systems (Dubois & Gadde, 2002). BIM technologies are digital systems linking designers in a shared space and thus are intended to tighten the coupling in projects. How to merge a collaborative, inter-organizational system with a loosely coupled system is an interesting area in need of further inquiry, which is in focus in this thesis.

Linderoth et al. (2011) have argued that "self-centric" ICT deployment with little investment in collaborative technologies represents the core problem of today's construction industry. The research review that was conducted identified few studies inquiring into the social and technical aspects of collaborative work; thus, how to overcome the "self-centric" behavior in ICT deployment is little understood. The extent to which ICT deployment behavior is influenced by the production environment typical for the construction industry requires further scrutiny. This thesis contributes to the body of BIM deployment literature in the following areas:

- Multi-actor-level studies of BIM's role in collaboration informed by inter-organizational systems literature (Robey et al., 2008);
- Studies exploring the influence of industry features (Chiasson & Davidson, 2005) and the nature of projects (Baccarini, 1996) on BIM deployment; and
- Studies exploring both the technical and social aspects of collaborative BIM-based work, similar to that which has been suggested by Baxter (2008).

2.3 Configuration Analysis Perspective

Configuration analysis is a perspective developed for the study of IOIS. IOIS facilitate business transactions and business processes between two or more organizations (Cash & Konsynski, 1985). In IOIS research, "numerous theories have been used and […] no single theory has dominated" (Robey et al., 2008). However, studies of organizational IOIS adoption are primarily informed by DOI theory and TAM (ibid.). As shown in the previous chapter, DOI and TAM are also applied in the context of BIM deployment research (Peansupap & Walker, 2005, 2009; Kubicki et al., 2009; Suermann & Issa, 2009). The value of these theories is that they help in explaining the antecedents of technology diffusion, such as the willingness to learn technology, colleague help, and organizational support.

While some scholars argue that DOI is well suited to explaining the relevant antecedents of organizational IOIS deployment (Robey et al., 2008), others find that classical DOI theory (Rogers, 2010) is best suited for the study of technology, having an internal locus of impact, and being adopted by a single organization (Lyytinen & Damsgaard, 2001, 2011). Studying the behavior of singular, independent adopters does not recognize the need for alignment among "families of interdependent organizations with their technological capabilities and their strategic and structural arrangements as wholes" (Lyytinen & Damsgaard, 2011, p. 502). Moreover, it has been argued that DOI has limited explanatory power in providing an understanding of why the "same technology within the same population is adopted in different ways" (ibid., p. 506).

The configuration analysis perspective has been developed to compensate for this gap in traditional analysis based on DOI. The goal was to provide a complimentary perspective enabling scholars to look beyond single adopting organizations in IOIS adoption, and, in contrast, to study a set of organizations that are interconnected through their IS. The configuration analysis perspective has been introduced by Lyytinen and Damsgaard (2011). Its origins can be traced back to organizational theory, where organizations and markets are defined as interconnected structures (Coase, 1937; Williamson, 1979). Configuration analysis offers a structured way in which to explore both the social and technical elements that are relevant to IOIS deployment at the inter-organizational level. A configuration can be seen as an arrangement of parts and elements bound together by "a central, enduring theme that unifies and organizes them" (Miller, 1987, p. 697). In practice, organizations seek to configure their technology, policies, systems, and routines in a coherent way (Miller, 1996). The configuration analysis perspective applies "configuration thinking" to inter-organizational systems adoption.

The core concepts and terminology of the configuration analysis approach suggested by Lyytinen and Damsgaard (2011) are presented in what follows. The term *adopter configuration* was coined to describe arrangements made among the organizations to coordinate their collaborative IOIS-based work. The authors provide the following definition: "We define adopter configuration as a set of interrelated IOIS adopters united by an organizing vision and associated key functionality, which determine the structure, mode of interaction and appropriation available for the participating organisations" (p. 3). Adopter configurations are conceptualized along five social and technical dimensions: (1) organizing vision, (2) key functionality, (3) structure, (4) mode of interaction, and (5) mode of appropriation. The definition of each dimension of an adopter configuration is presented in Table 2-1. Results of IOIS adoptions differ significantly, even if they involve similar technology and take place in comparable contexts. The authors suggest that these deviations can be partially explained by differing local configurations among the adopters (Lyytinen & Damsgaard, 2011). The five key elements of an adopter configuration are interrelated and should be studied collectively. The authors claim that this provides a solid understanding of the alignment among the organizations working based on the shared system.

Table 2-1 *Key Elements of an Adopter Configuration (Lyytinen & Damsgaard, 2011)*

Organizing vision	Conveys a persuasive cognitive model of how the IOIS help organize better inter-organizational structures and processes.
Key functionality	Defines, in turn, the scope and content of data exchanges and related business functionality in terms of the contents of messages, their choreography, and coverage.
Structure	Defines the scope and volume of structural relationships among participating organizations.
Mode of interaction	Nature of relationships between the participating organizations as defined by the IOIS.
Mode of appropriation	The scope and intensity of potential effects of adopting the IOIS for the participating organization.

An *adopter population* is defined as the set of all organizations that have "participated (or could have participated) in at least one adopter configuration" (ibid., p. 4). An *adopter ensemble* is defined as the set of organizations working based on the shared IOIS. An adopter ensemble is a subset of the adopter population. Adopter ensembles are suggested as the unit of analysis in configuration analysis studies. A visual representation of what is meant by the terms adopter population and ensemble can be found in Figure 2-2. Each square in Figure 2-2 depicts an organization, black squares represent adopters of the IOIS, whereas white squares represent those not yet working based on the IOIS. All firms (e.g. squares) within a circle represent the population of organizations having the potential to participate in the IOIS (e.g. adopter population). Perhaps the most important difference between traditional approaches (e.g. based on DOI) and configuration analysis for the study of IOIS is highlighted in Figure 2-2. On the left side in Figure 2-2 (I), a traditional approach to the study of IOIS based on single adopting organizations is presented. On the right side in Figure 2-2 (II), three examples of adopter ensembles typically found in inter-organizational systems are depicted (labeled a, b, and c).

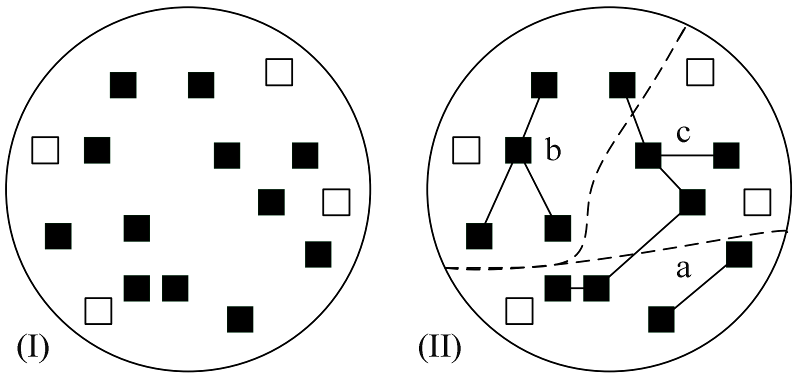


Figure 2-2. IOIS adoption showing: (I) Traditional analysis (II) Configuration analysis with a) a dyadic configuration; b) a hub-and-spoke configuration and; c) a configuration across several industrial sectors (Lyytinen & Damsgaard, 2011).

The ensembles are subsets of the adopter population (circle). The dotted lines in Figure 2-1 (II) illustrate different industrial sectors (e.g. architects, engineers, client, contractor, and specialist suppliers). The identified ensembles a, b, and c differ in a variety of aspects. For instance, (a) represents a dyadic type of IOIS linking only two organizations. Ensemble (b) is a hub and spoke configuration where one organization acts as a central information hub. Ensemble (c) is an IOIS configuration linking several industrial sectors. Lyytinen and Damsgaard (2011) claim that the type of IOIS setup matters, as each setup follows its own logic.

Why has this theory been chosen?

In BIM deployment literature, we find multiple studies theoretically ingrained in ICT diffusion theory focusing on the behavior of single adopters of BIM technology. In more recent work, the focus has shifted toward studying networks of organizations interrelated by their BIM systems, for instance, based on ANT or boundary objects theory (Gal et al., 2008; Linderoth, 2010). According to Gregor's taxonomy of IS theories, configuration analysis can be seen as a theory for explaining how and why things happen (Gregor, 2006).

Applying configuration analysis to BIM phenomena complements prior work by explaining how and why things happen at the inter-organizational level. The value of configuration analysis is in its strength to analyze, explain, and understand the alignment among a set of organizations that are interrelated by their IS. There is a clear need for further studies exploring the social and technical aspects at the inter-organizational level. One advantage of configuration analysis over theories such as ANT and boundary objects is that it has been developed for the study of IOIS deployment, meaning that all of its conceptualizations are specific for the study of this type of systems . The advantage over DOI is that the analysis is not directed at a "focal firm" and its network, but at the network of firms itself. Thus, applying configuration analysis in this way provides some useful insights about collaborative BIM work beyond that which has been presented in the extant literature.

Configuration analysis provides a structured approach for the study of the key issues emerging in collaborative BIM-based work. Applying this view in this project in the wood-based building industry helps in addressing the research sub-questions by identifying the current state of collaborative BIM-based work (SQ1), its barriers (SQ2), and required changes (SQ3). By applying this research approach, practical and conceptually important insights about collaborative BIM-based work and the issues emerging among organizations can be derived.

2.4 Cooperative Capability Analysis Perspective

It is only when a firm possesses the necessary organizational IT/IS capabilities and puts them to "productive" use that the advantages of IS can be realized (Wade & Hulland, 2004). This line of thinking has its origins in the resource based view (RBV) of the firm in which the resources at a firm's disposal can be turned into a competitive advantage (Barney, 1991). RBV-based studies started to appear in IS research in the mid-1990s (Wade & Hulland, 2004). In the IS literature, the resources required to deploy IS are frequently referred to as IT/IS capabilities. In general, organizational capabilities have been defined as "complex bundles of skills and collective learning, exercised through organizational processes that ensure superior coordination of functional activities" (Day, 1994, p. 38).

Day (1994) has conceptualized three types of capability processes: inside-out, outside-in, and spanning. In the context of IS deployment, inside-out capabilities can be seen as the internally focused "information processing capability" of an organization, consisting of the available IT infrastructure, IT skills of the employees, and internal IT cost control (Wade & Hulland, 2004). Outside-in capabilities include, among others, a firm's activities with which it engages in its business environment, such as IS business partnerships (ibid.). Spanning capabilities can be seen as those capabilities that are needed to align, manage, and plan IT/IS across all internal and external operations (ibid.). A typology of frequently discussed capabilities in the IS literature can be found in Table 2-2.

Table 2-2 *A Typology of IS Capabilities (Wade & Hulland, 2004)*

Inside-Out	Spanning	Outside-In
IS infrastructure IS technical skills IS development Cost-effective IS operations	IS business partnerships IS planning and change management	External relationship management Market responsiveness

Inter-organizational systems deployment depends upon the IT capabilities of several organizations. All firms partaking in the shared IOIS would need appropriate IS infrastructure, technical skills, the ability to manage IS, and, most importantly, the ability to build lasting IS partnerships. This is in line with what has been suggested by Tyler (2001), in that participating firms would need technological and cooperative capabilities. The availability of the aforementioned capabilities depends on a firm's unique history and experiences, past activities, capabilities to learn, and its financial and technological assets (ibid.). Cooperative and technical IT capabilities cannot easily be copied, and once achieved, they might lead to a sustainable competitive advantage (Santhanam & Hartono, 2003).

It has been argued that that current IOIS research could be strengthened by conceptualizing IT/IS capabilities in a more dynamic way, similar to the dynamic capabilities paradigm used in the strategic management literature (Teece, Pisano, & Shuen, 1997). In dynamic capabilities research, the focus is on "how firms learn new skills, internal and external forces that enable and constrain learning, and environmental reactions to competition for resources" (Robey et al., 2008, p. 511). From this perspective, it is considered important that firms mobilize their resources "sooner, more astutely, and more fortuitously" than others do (Eisenhardt & Martin, 2000, p. 1117).

Collaborative performance measures the extent to which organizations mobilize their resources to collaborate based on a shared system. It is a "compound metric of collaborative effectiveness and collaborative efficiency" (Kristensen & Kijl, 2010, p. 60). Efficiency refers to the number of resources consumed and gained by collaborating and effectiveness refers to the degree to which using the IOIS aids in goal achievement. Collaborative performance can be seen as a measure for alliance capabilities in collaborative work (Blomqvist & Levy, 2006). Several frameworks for the assessment of collaborative performance can be found in the literature. These frameworks (1) provide a conceptualization of collaborative capabilities, (2) aid in the understanding of collaboration issues, (3) can guide the selection of ICT solutions, and (4) provide an understanding of a baseline situation in collaborative work (Munkvold, Weiseth, & Larsen, 2009).

Why has this theory been chosen?

Teamwork based on a shared system such as BIM is hard to accomplish when organizational IT/IS maturities differ (Porwal & Hewage, 2013). Especially in project organizations, with ever changing constellations of actors, different levels of organizational BIM capabilities are likely to be found (Linderoth et al., 2011). Recognizing the importance of evenly distributed BIM capabilities, practitioners and especially large construction clients have begun to select their project teams based on prior BIM experience (McGraw-Hill, 2012).

Accordingly, researchers have developed advanced assessment tools for the evaluation of corporate collaborative BIM capability and maturity (Succar et al., 2012). AEC researchers study the level of organizational BIM uptake and whether or not this uptake is moving toward integrated practice. One example of a BIM-specific capability assessment model is the interactive BIM capability and maturity model (I-CMM) (McCuen, 2008). This model is, in essence, a further development of the capability maturity model (CMM) developed by the Software Engineering Institute (ibid.). A second model that has been widely applied to understand BIM performance is the building information modeling maturity index (Succar et al., 2012). These models are useful for understanding the degree and intensity achieved in collaborative BIM-based design. Moreover, they allow for determining the maturity with which designers execute their work.

According to Gregor's taxonomy of IS theories, cooperative capabilities can be seen as a theory for explaining how and why things happen (Gregor, 2006). This perspective has been chosen for its strength in enabling a comparison of collaborative BIM-based performance. It is useful for identifying the degree of sophistication with which a team collaborates in a project. The focus in this project is to compare collaborative performance across different types of projects to explore how the collaboration is influenced by project characteristics.

2.5 Diffusion of Innovations Theory

DOI theory has been developed to explore the underlying mechanisms of how and why an innovation becomes diffused in a social system. It can be traced back to Rogers' seminal 1962 book titled *Diffusion of Innovations*. Rogers, an agricultural scientist at Iowa State University, found that the diffusion process of agricultural innovations (e.g. hybrid seed corn), driver training among schools, and antibiotic drugs among medical doctors all followed a similar pattern (Rogers, 2004). Based on this discovery, he formulated a generic diffusion model for the study of all kinds of innovations that are useful to many academic disciplines (ibid.). Rogers defined innovation as "idea[s], practice[s] or object[s] that [is/are] perceived as new by an individual or unit of adoption" (Rogers, 2003, p. 35) and diffusion as "the process through which an innovation is communicated through certain channels over time among the members of a social system" (Rogers, 2003, p. 23).

Rogers's theoretical model has received wide research attention across a range of disciplines including sociology, economics, organizational research, and IS (Fichman &

Kemerer, 1999). DOI has been applied to study technical, process, product, and administrative innovations. Researchers study different dimensions and topics such as the diffusion process itself or corporate innovativeness. Researchers interested in the diffusion processes seek to understand “What determines the rate, pattern and extent of diffusion of an innovation across a population of potential adopters?” (Fichman, 2000, p. 2). Others more interested in the organizational innovativeness study “What determines the general propensity of an organization to adopt and assimilate innovations over time?” or “What determines the propensity of an organization to adopt and assimilate a particular innovation?” (ibid., pp. 2–3).

DOI is widely applied in IS research for the study of IS diffusion at the organizational level (Robey et al., 2008). Rogers’ (2003) classical DOI theory is considered as the dominant paradigm informing organizational IOIS adoption studies (Robey et al., 2008). IS researchers found early on that diffusion theory would be a good fit to capture the important antecedents of organizational IS diffusion (Cooper & Zmud, 1990; Moore & Benbasat, 1991). Rooted in DOI, scholars have developed diffusion models for IS implementation. One example is the work by Cooper and Zmud (1990), in which they advanced a staged IT implementation model ranging from initiation, adoption, adaptation, acceptance, routinization, to the infusion of IT. The final stage of IT infusion is achieved when “an innovation’s features are used in a complete and sophisticated way” (Fichman, 2001: p. 430, cited in Robey et al., 2008). Depending on its application, DOI could be classified as a theory to explain, predict, and provide testable propositions of an implementation success or technology adoption (Gregor, 2006). It is widely applied to develop causal relationships where the dependent variable is the diffusion of an IOIS, which can be conceptualized in different stages (Robey et al., 2008).

Organizational IOIS diffusion is influenced by external environment, organizational readiness, innovation characteristics, perceived benefits, transaction characteristics, resource dependence, network externalities, and cultural/institutional forces (Robey et al., 2008). Despite DOI’s traditional focus on single organizations, IOIS studies “take the analysis of adoption and diffusion beyond individual firms to the surrounding network of firms” (ibid., p. 503). Studying network externalities or institutional forces on IOIS diffusion requires researchers to understand inter-organizational relationships surrounding the organizations. Research on how organizational IOIS diffusion is influenced by competitive pressures or social networks can be found in the IS literature (e.g. Basole, Seuss, & Rouse, 2012).

Some researchers have argued that DOI's focus on the ICT diffusion process by single adopters represents a weakness for the study of complex, networked technology (Lyytinen & Damsgaard, 2011). Moreover, some argue that DOI research suffers from a "pro-innovation" bias rooted in its assumption that it is a good thing to diffuse and adopt an innovation in a social system (Rogers, 2003). However, in spite of these concerns, DOI studies appear to provide useful explanations regarding the antecedents that are relevant for organizational IOIS adoption (Robey et al., 2008).

The core concepts and terminology of the DOI theory suggested by Rogers (2003) are presented in what follows. Rogers argues that the characteristics of the social system and its context need to be considered when studying the diffusion of an innovation. He argues that the decision as to whether or not an innovation is adopted in a social system can either be made voluntarily or forced upon a unit of adoption. Rogers suggests that decisions to adopt an innovation differ in their degree of voluntariness ranging from (1) optional, (2) collective, to (3) authority innovation decisions. An optional innovation decision is defined as a decision that is made by an individual who is in some way distinguishable from others in a social system. A collective innovation decision is made collectively by all of the individuals in a social system. An authority innovation decision is made for the entire social system by a few individuals in positions of power and influence.

Rogers advanced a stage model describing the process through which adopters arrive at the decision to adopt or reject an innovation. The adoption decision process is conceptualized along five stages: (1) knowledge, (2) persuasion, (3) decision, (4) implementation, and (5) confirmation. Knowledge here refers to the situation in which an individual learns about the existence of the innovation. Persuasion refers to the process of building a favorable or unfavorable opinion about the innovation. Decision refers to the event in which the potential adopter makes the decision to adopt or reject the innovation. Implementation refers to the activity involved in putting an innovation to use. Confirmation refers to the activities in which an adopter evaluates and judges the success of the adoption.

Some actors in the social systems are of particular importance during the adoption process. Individual opinion leaders and change agents may have the power to "sway the choice" from adoption to rejection. Opinion leaders are prestigious individuals whose opinions carry more weight than those of others in their social system. Change agents are individuals advocating the need for change and innovations, and can become important actors by influencing the adoption decision of an adopting firm.

Innovations can be diffused in different ways, and Rogers distinguishes between centralized and decentralized diffusion systems. A centralized diffusion system exists when a central actor takes most decisions about the innovation and its dissemination. A centralized diffusion approach can be seen as a “top-down” diffusion method, leading to potential disadvantages including a high potential for user resistance and low applicability of the innovation in some local settings. A decentralized diffusion approach entails the development and diffusion of innovations in more confined settings. Innovations are developed and diffused in local settings. Advantages of decentralized diffusion include local control and motivation and disadvantages include the risk of too little quality.

The diffusion of an innovation depends on the extent to which members of a social system perceive it as important. Rogers argues that individual actors possess different degrees of “willingness” to adopt and work with innovations. He suggests that individuals exist along a spectrum ranging from technological “innovators” to “laggards,” depending upon their socioeconomic status. Members of each category have different general attitudes toward an innovation, as shown in Table 2-3. Naturally, opinion leaders (e.g. innovators) would be quick to adopt a new innovation whereas laggards would adopt an innovation last.

Table 2-3 *Five Categories of Individual Innovativeness (Rogers, 1995)*

Innovators	Venturesome, educated, multiple information sources
Early adopters	Social leaders, popular, educated
Early majority	Deliberate, many informal social contacts
Late majority	Skeptical, traditional, lower socioeconomic status
Laggards	Neighbors and friends are main information sources, fear of debt

Several attributes of the innovation itself define its rate of adoption; namely, “relative advantage, compatibility, complexity, trialability, and observability” (Rogers, 2003). Relative advantage is defined as “the degree to which an innovation is perceived as better than the idea it supersedes” (Rogers, 2003, p. 229). Compatibility is a term used to define the “degree to which an innovation is perceived as consistent with existing values, past experiences, and needs of potential adopters” (ibid., p. 15). Complexity describes the difficulty of using and understanding the innovation. Trialability refers to a potential adopter’s chance of trying out and changing the new innovation before it is adopted. Last, observability refers to the visibility of the new innovation. If an innovation could be observed elsewhere by potential adopters, their decision may be better informed. An example of DOI-based research in the field of building construction is the work by Peansupap and Walker (2005, 2006a, 2006b). Based on a quantitative survey among construction practitioners in Australia, they found eleven individual, environmental, managerial, and technological diffusion factors that are useful for driving the rate of ICT adoption in the construction industry. An overview of the factors proposed by Peansupap and Walker is presented in Table 2-4. This provides a good starting point to understand the processes leading to BIM diffusion.

Table 2-4 *Diffusion Factors for ICT in Construction Projects (Peansupap & Walker, 2005)*

Individual factors	Supporting individual/personal characteristics Clear benefits of ICT use Positive feelings toward ICT use Negative emotions toward ICT use (negative factor)
Environment factors	Supporting open discussion environment Supporting colleague help
Management factors	Supervisor and organizational support Professional development and technical support Supporting tangible and intangible reward
Technology factors	Supporting technology characteristics Frustration with ICT use (negative factor)

Why has this theory been chosen?

DOI literature serves as a natural foundation with which to explore why actors succeed in BIM adoption and use. First, it has proven its value in explaining the relationships between the IOIS diffusion process and its antecedents (Robey et al., 2008). Second, newer versions of this theory also focus on network externalities, affording the study of networked technology such as BIM. Last, it has been applied in the context of building construction, which serves as a starting point for further work in this area (Peansupap & Walker, 2005, 2006a, 2006b). However, Lyytinen and Damsgaard (2001) have suggested that complex, networked IT solutions should be understood as “socially constructed and learning intensive artifacts, which can be adopted for varying reasons within volatile diffusion arenas” (p. 173). Applying DOI to study complex IT such as BIM would then be best accomplished by prioritizing accuracy over generality (ibid.). This calls for collecting rich data based on an interpretive research strategy to develop an in-depth account of the antecedents of BIM deployment.

My main reason for choosing this theory is that it has the capability of explaining what it takes to deploy BIM. It provides a structured means with which to describe the processes leading to BIM deployment and collaborative work. Further, it is useful to explicate the type of adoption decision, the role of "change agents," the role of "opinion leaders," and the mechanics of an adoption. In this thesis, DOI has been applied in the study of a construction project, which can be seen as an example of advanced BIM-based practice, to explain what drove the project team to collaborate. This will enable us to provide other practitioners who continue to struggle with this new technology with lessons learned from advanced BIM practice.

2.6 Connecting the Perspectives

Combining the strengths of these three theoretical perspectives can provide a comprehensive understanding of BIM deployment for collaborative work. Several examples of research in which combinations of theories have been applied can be found in the literature. One such study is the work by Marks, Mathieu, and Zakkaro (2001), in which they explore team behavior based on uniting several research streams. An example of such work in IS is the study by Riemschneider, Harrison, and Mykytyn (2003), who combined the theory of planned behavior (TPB) and TAM to research IT adoption in small and medium-sized organizations.

The common ground of these three perspectives is that all of them depart from the similar assumption that IT use is a socio-technical phenomenon. The configuration analysis perspective considers both social and technical aspects of collaboration such as the key organizing vision and the functionality of a system. The cooperative capabilities perspective is applied to the study of both social and technological capabilities such as IS business partnerships and IS infrastructure. The DOI perspective devotes attention to a combination of social and technical diffusion factors such as positive feelings toward ICT use and the technical characteristics of a system. In what follows, I summarize why the three perspectives were used in this thesis.

(1) Configuration analysis works well to explore the inter-organizational "configuration" for IT-enabled collaborative work. It is a useful lens through which to explore how a set of organizations working based on BIM in a construction project arranges their collaborative work and the issues experienced. It further explains both the social and technical aspects of collaborative BIM-based design. Applying configuration analysis to study a project executed by the wood-based building industry is useful for answering SQ1 and SQ2 in this project. In brief, it is concerned with the alignment among organizations.

(2) The cooperative capabilities lens works well to understand the overall collaborative performance displayed by a project team in BIM-based work. This lens can be applied to explore variances in collaborative performance across projects. When applied in a cross-case analysis, it can be used to identify whether collaborative performance is linked to project complexity. This is important for understanding SQ1 and SQ2.

(3) The DOI perspective can be applied to explain the antecedents of BIM technology diffusion. When used to study advanced BIM-based practice, DOI can aid in explaining why a project team succeeds in collaborative design. DOI is a useful lens through which to explain how current challenges in integrated design can be overcome, and thus, it contributes to answering SQ3.

As shown in Table 2-5, all three lenses contribute in a unique way to understanding the empirical phenomenon, which is BIM-based collaborative work in a construction project. Further, Table 2-5 explicates the nature of the explanations provided by each theory, the reasons as to why the theories were chosen for this study, and how the theories are related to the research questions asked in this thesis.

Table 2-5 *Complementary Role of the Selected Theories*

Theories	Nature of Explanation	Why It Has Been Chosen	RQ
(1) Configuration analysis	(a) Explains inter-organizational systems adoption (b) Studies several technical and social dimensions emerging in inter-organizational IT-based collaboration (c) Unit of analysis is the adoption units (a set of organizations interconnected by IS)	(a) Has the strength to explain collaborative BIM work at project level (b) Allows for identifying a variety of issues emerging in collaborative BIM-based work (c) A multi-actor perspective is useful to identify the current use of BIM for integration in a construction project	SQ1* and SQ2*
(2) Cooperative capabilities	(a) Explains the competencies relevant for information processing, communication, knowledge transfer, etc. (b) Inter- and intra-unit level of analysis possible	(a) Has the strength to explain collaborative performance in construction projects (b) Useful for identifying the degree of sophistication displayed by actors working collaboratively based on BIM technology (c) Useful for cross-case comparison of collaborative performance in BIM-based design	SQ1* and SQ2*
(3) Diffusion of innovations theory	(a) Explains the diffusion of IT in a social system (b) Takes into account the type of adoption decision (c) Explains factors leading up to an IT adoption	(a) Useful to understand the factors leading to successful BIM diffusion in a project situation where actors collaboratively use BIM (b) Results of such analysis can provide learning for other settings	SQ3*
* SQ1: What is the current state of BIM adoption for integration in the wood-based building industry? SQ2: What are the predominant social, environmental, and technical barriers for the adoption of BIM in the industry? SQ3: What changes will be required with respect to work processes and interaction between the actors in the industry to achieve improved design information sharing through the use of BIM?			

3 Research Approach

The research approach presented in this chapter can be seen as the overall strategy chosen to integrate the different components of the study in a coherent and logical way. The research problem, in conjunction with ontological and epistemological assumptions, shaped the research design of this study. This chapter explicates the selected research approach taken in this project. First, the research perspective underlying this work is clarified. Second, the research methods are presented. Third, the data-collection, reduction, and analysis methods are presented. Last, a quality insurance check of the overall research approach is conducted.

3.1 Research Perspective

This thesis is founded on the ontological assumption that the form and nature of reality is a social construction (Berger & Luckmann, 1966). The term *social construction* refers to a tradition of scholarship that perceives reality as local, specific, and varying between individuals. Social construction builds on the philosophical assumption that we are being constructed by the world we live in, and, at the same time, we construct the world based on our own experiences and backgrounds. Thus, the ontological view underlying my work can be seen as constructivist. Having a major impact on the development of social constructionism, Heidegger argued that “Men will know, […], that which is incalculable, only in creative questioning and shaping out of the power of genuine reflection” (Delanty & Strydon, 2010, p. 151). Heidegger’s branch of philosophy, namely phenomenology, suggests the study of human experience as articulated via varied languages and discourses.

Consistent with my ontological view, the epistemological research perspective applied in this study is interpretive. Interpretive reasoning has become a well-established part of sensemaking in IS research (Walsham, 2006). Interpretive researchers believe that social phenomena can only be understood by studying individuals’ views of their social world. Interpretivism as a line of thought originates in Max Weber’s writings and his “Verstehen” or “understanding” concepts, where knowledge is generated through an interpretive understanding of social action (Weber, 1925). Doing interpretive research requires referencing a person’s background and understanding the subjective meanings that the person has about the world around him-/her- self (Fitzgerald & Howcroft, 1998; Orlikowski & Baroudi, 1991).

3.1.1 Role of the researcher. As discussed by Walsham (1995), pursuing the "difficult task to gain access to other people's interpretations" (p. 77) requires researchers to reflect upon their own role in this process. Researchers can take on two different roles in an interpretive inquiry; namely, that of an outside observer and that of an involved researcher (ibid.). The merit of being an involved researcher lies in the possibility of being able to observe the day-to-day happenings in an organization by having direct and personal access to the research setting. On the other hand, unless they work undercover, involved researchers will not be regarded as ordinary employees, and will likely not be able to access "sensitive" data. Being an outside observer also confers advantages. Outside researchers are not beholden to any of the people, groups, or organizations under study. This allows for outside observers to conceptualize people's interpretations more freely and to provide a fresh perspective. Moreover, people are likely to be outspoken and frank in expressing their opinions to persons not having a personal stake in their organization. A downside to studying a group to which one is not a member is the limited access to the field, constraining the ability for getting a direct, internal, and personal view of the organization (ibid.).

My role as a researcher in this project has been that of an outside observer. My study is focused on phenomena emerging across several organizations. Given this focus, being an outside observer had several advantages for my work. First, the inquiry favored a role that preserved the distance from single organizations to gain an overview of the inter-firm collaboration. Second, solving the research task at hand required not having a personal stake in any of the organizations, but rather, obtaining a balanced view of interpretations across several firms.

3.1.2 Role of theory. Theory is used in this thesis as an initial guide to design the data collection (Walsham, 1995). The theories presented in Chapter 2 -namely configuration analysis, cooperative capabilities, and DOI- have all inspired the design and structure of the research work undertaken in this thesis. Several examples of a priori use of theory in interpretive IS work can be found in the literature (Boland, 1991; Walsham & Sahay, 1999). However, this way of using theory carries the risk of "only see[ing] what theory suggests" and thereby one can overlook new issues of exploration (Walsham, 1995). A "considerable degree of openness" (ibid., p. 76) to new findings is necessary to conduct proper interpretive research. The main choices made regarding the research perspective applied are presented in Table 3-1.

3.1.3 The research strategy. The research problem addressed in this study is socio-technical in nature. The overall research question asked is how BIM can support integrated practice in the wood-based building industry. Answering this question requires an in-depth understanding of BIM technology, the experiences of the human stakeholders, and the differences across construction project situations. The research problem, the questions asked, the theories chosen, and the underlying interpretive perspective all shape the choice of research methodology. When producing interpretive research, collecting qualitative data is widely perceived as a necessity (Klein & Meyers, 1999). Case study research is the most common qualitative method used in IS research (Orlikowski & Baroudi, 1991; Paré & Elam, 1997; Walsham, 2006). Moreover, in-depth case studies are widely applied by IS researchers of the "interpretive school" to facilitate their investigations (Walsham, 1995). The outcomes of this work are often narratives that are thick in description (Boland, 1991; Lee, 1994; Myers, 1994).

The research strategy chosen to guide the inquiry in this research is the case study approach. There are several reasons why a case study approach seems to be a good fit for the purpose of this research. First, interpretive case studies afford the investigation of "sticky, practice based problems where the experiences of the actors are important and the context of action is critical" (Benbasat, Goldstein, & Mead., 1987, p. 370). Second, an in-depth case study approach suits the investigation of relationships between people, organizations, and technology (Orlikowski & Baroudi, 1991). Third, case studies aid researchers in developing an "understanding [of] the whole [social reality] by understanding all the little bits that make up the whole" (Myers, 1994, p. 191). Last, the research question pursued in this thesis ("How can building information modeling support practice in the wood-based building industry?") is an exploratory "how" question, and the case study method is perceived as well suited for studying those types of questions (Walsham, 1995; Yin, 2009). All the aforementioned aspects make the interpretive case study approach a good fit for this thesis.

A multiple case study design was chosen in this project to maximize the analytical leverage of the research. The main advantage of a multiple case study design over a single case study design is that this allows for studying the phenomenon in multiple contexts. As argued above, case studies are useful for providing an "understanding of the context of the information system, and the process whereby the information system influences and is influenced by the context" (Walsham, 1993, pp. 4–5). Contextualizing BIM-based work by conducting a set of case studies in different construction projects enhances the understanding of how and why the BIM deployment differs. Moreover, elucidating the differences in people, technology, organizations, and projects across cases is useful in achieving a more general understanding of the antecedents of BIM deployment (Klein & Myers, 1999). The next chapter will provide a detailed account on the cases selected. Table 3-1 presents an overview of the elements comprising the research perspective applied in this thesis.

Table 3-1 *Outline of the Research Perspective Applied*

Elements of the Research Perspective	Stance Chosen in This Research
Philosophy	Phenomenology
Ontological assumption	Social constructivism
Epistemology	Interpretivism
Role of the researcher	Outside observer
Role of theory in this research	An initial guide for data collection and analysis
Research strategy	Multiple case studies

3.2 Introducing the Cases

At the outset of the PhD project, it was decided that BIM deployment in the local wood-based building industry should be the locus of this research. Moreover, there was a plan to compare several different construction projects by applying a multiple case study research strategy. The following explicates the rationale for selecting the cases and how, together, they contribute to an increased understanding of BIM-based work in the wood-based building industry. In this, I will refer to the research sub-questions guiding the inquiry: (SQ1) What is the current state of BIM adoption for integration in the wood-based building industry?; (SQ2) What are the predominant social, environmental, and technical barriers for the adoption of BIM in this industry?; and (SQ3) What changes will be required with respect to work processes and interaction between the actors in the industry to achieve improved design information sharing through the use of BIM? Additional information on the cases can be found in the articles presented in Appendix C and in Chapter 4.

Three different cases of BIM-based work were chosen: a residential project, a public library project, and a hospital development (hereafter referred to as Case A, B, and C). All cases used in this thesis have been identified by using a snowball or chain strategy (Patton, 2002). A snowball or chain approach “identifies cases of interest from people who know people who know people who know what cases are information-rich, that is, good examples for study, good interview subjects” (ibid., p. 243). The informants or “people who know” chosen to assist the sample selection within this research project were the public construction and property managers of Vest-Agder and Aust-Agder counties, and the educational director of the industry-led organization

BuildingSMART© Norway. These persons have in-depth knowledge about recent and ongoing construction projects in Agder and Norway. The Vest and Aust-Agder county officials have participated in the initiation of this doctoral project in close cooperation with leading representatives of the local wood-based building industry. The process of selecting Cases A and B has been advanced in close collaboration with the county municipalities and several local organizations affiliated with the regional Agder Wood initiative (www.agderwood.no). The educational director of BuildingSMART® Norway aided in the identification of Case C based on his extensive knowledge of BIM use in the Norwegian construction industry. Figure 3-1 provides an impression of the case projects chosen and analyzed in this thesis.

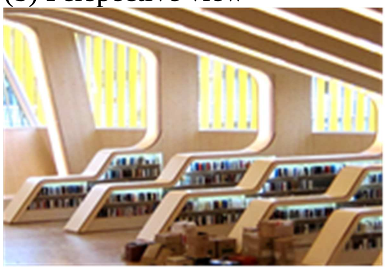
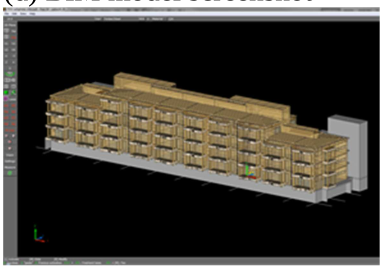
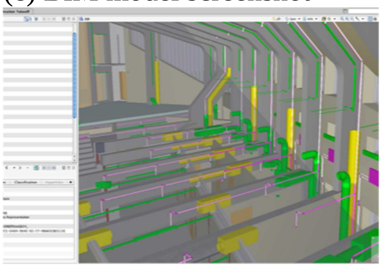
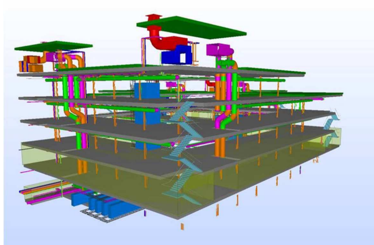
Case A: Residential Project	**Case B: Library Project**	**Case C: Hospital Project**
(a) Perspective view 	(b) Perspective view 	(c) Perspective view 
(d) BIM model screenshot 	(e) BIM model screenshot 	(f) BIM model screenshot 

Figure 3-1. Visualizations of the case projects showing perspective-view renderings of the case buildings (a–c), and screenshots of the BIM models used (d–f) ([a;d] ©2013 Trebyggeriet; [b;e] ©2013 Helen&Hard; [c;f] ©2013 HelseSørØst; all used with permission).

A combination of a "typical case," an "extreme or deviant case," and "snowball" sampling strategies (Miles & Huberman, 1994) was applied in the case selection. Cases A and B were chosen as representative examples for BIM-based work in the wood-based building industry executed by the professionals usually involved in this type of projects (i.e. client, architect, consultants, and manufacturers of wooden components). Choosing typical cases of BIM-based work in the wood-based building industry was useful for developing an understanding of the current state, and the predominant barriers experienced in BIM deployment in this sector of the construction industry (SQ1, SQ2). Moreover, these cases were identified through "snowballing" by asking those who knew of good and information-rich examples of BIM-based work in this industry. Analyzing an extreme case of BIM deployment, in which the system was used to the fullest, enabled an understanding of how current practice observed in the wood-based building industry could be improved (SQ3). The third project (Case C) was a case of BIM deployment in the general AEC industry, and was chosen for the high level of sophistication with which the project design team operated based on BIM. It can be considered an atypical or extreme case of BIM deployment, as it was regarded by the team itself, and the educational director of BuildingSMART© as the most advanced case of BIM deployment in Norway so far.

Moreover, as can be seen in Figure 3-2, all three cases differed in their levels of design complexity. While Case A was a more or less "industry standard" type of housing development (Figure 3-2a and d), Case B was an ambitiously designed public library building with "shifting shapes" (Figure 3-2b and e), and Case C was a large hospital facility with technically complex installations typical for this kind of development (Figure 3-2c and f). Studying a set of cases varying in design complexity allowed for exploring if BIM deployment is influenced by the characteristics of a construction project. In the following, the three cases are introduced.

3.2.1 Case A: The residential building project. In the initial stage of the PhD project, I was on the lookout for a typical case of BIM deployment taking place in the local wood-based building industry to capture the current state and the predominant issues experienced in this work (SQ1 and SQ2). In February 2011 (two months into the PhD project), I met with several construction experts who were representatives of local industry, government, and academia at the University of Agder's Grimstad campus. In this meeting, I presented the initial ideas about the research project and I asked the participants for their considered opinion on how to find an interesting and typical case of BIM deployment. An employee of a local wood-based construction firm suggested studying a residential construction project executed based on BIM. Further, he stated that he would be willing to facilitate access to the case. Once initial access had been granted, all of the key players in the project could be identified based on a snowball chain approach.

The setting for Case A was a wood frame, multi-story, low-energy housing development in the Bergen area of Norway. The project comprised the construction of three apartment buildings consisting of one hundred apartment units. While the design of the buildings can be seen as modernist, it is characterized by an extensive use of repetitive shapes (Figure 3-2a and d). The buildings were produced in an industrialized manner, signified by an extensive use of furbished prefabricated elements (e.g. wall panels including installations and finishes). The elements were produced in a factory located in Kristiansand, Norway, and they were subsequently shipped to the construction site located roughly 500 km further north. A certain degree of site assembly was required, as the site needed to be prepared and the elements needed to be connected.

The group of organizations involved in the project consisted of the local, Agder-based element manufacturer who provided the initial access to the case, the client's organization, an architectural office, and four engineering consultancies, each covering a different area of expertise ranging from structural to fire-protection design. The firms were located in Norway, with five in the same city (Bergen) and one in a different region of Norway (Kristiansand), while the structural timber-engineering firm was located in Switzerland. The project was competitively tendered and the design team had never worked together in this exact constellation; however, some of the Bergen-based firms already knew each other from previous projects. Bi-weekly meetings were held in Bergen in which the designers coordinated their work. No video conference systems or similar support systems were deployed to facilitate the meetings. This practice precluded some designers, such as the Swiss firm, from regular participation in the project meetings.

Even though most of the design team had replaced their old 2D CAD systems with new BIM technology, some firms still worked based on 2D CAD. Examples of firms not yet working based on BIM technology were the geotechnical consultancy, the fire-protection engineer, and the client's firm. The BIM-capable organizations used a variety of different BIM applications to produce their work, many of which were products from the vendor Autodesk© (Table 3-2). The element manufacturer worked based on a system called Cadwork®wood, a BIM solution for wood construction. In addition to working based on BIM software, they deployed advanced CNC milling tools in the production of the wooden elements. The actors had different levels of maturity when it came to deploying BIM, and while some had extensive prior experience from collaborative BIM-based work (i.e. structural, electrical, and heating, ventilating, and air conditioning consultants), others were just beginning to explore the opportunities of BIM (i.e. the architect), or were still working based on 2D CAD (i.e. the fire-protection engineer). The work processes related to the exchange of design information in this project resembled, in essence, those typically found in traditional 2D-based construction projects. In cases where BIM software was deployed, it was used within organizations to automate the creation of single disciplinary models. The focus on BIM deployment lay rather on speeding up the production of drawings than on improving the collaboration with other team members.

3.2.2 Case B: The library project. The library project was chosen as a typical example of a project executed by the local wood-based building industry. Case A was an example of a project in which BIM, despite being widely available, was only sparsely deployed to facilitate collaborative work. When searching for a second case, I thus looked for a project promising data about a more active BIM-based collaboration. This was considered necessary to better identify the predominant issues emerging when BIM is actively deployed in collaboration (SQ1 and SQ2). In March 2012, roughly one year into the PhD project, I arranged for a meeting with the representatives of Vest-Agder and Aust-Agder counties and several industry experts. In this meeting, several candidate cases of BIM use in the local wood-based building projects were discussed. The construction of the new library building in Vennesla municipality in Vest-Agder surfaced as a case likely to offer data on the collaborative use of BIM. The design of the library was considered to be more complex when compared to the design of the residential buildings in Case A. The Aust-Agder county representative provided me with access to this case and introduced me to the architect in charge of the design of the library. This architect then introduced me to the other firms involved.

The project studied in Case B comprised the construction of a library, a café, meeting places, and administrative areas. The project can be seen as an architecturally complex and challenging project with gradually shifting shapes resembling hybrid structures (Figure 3-2b and e). The design was highly differentiated, as it consisted of numerous varied elements. The building's structure consists of 27 ribs made of prefabricated glue-laminated timber. Moreover, its roof, interior walls, and exterior cladding consisted of massive wood and plywood boards cut by using CNC milling tools. The building has received national and international attention, and it has been awarded several architectural design prizes (Uleberg, 2014). The design was created with the aid of BIM systems. The glue-laminated ribs, the massive-wood roof, and wall elements were prefabricated by two specialist manufacturers both located in different parts of Norway. The intensive on-site assembly work, where many unique parts needed to be brought together, was executed by a local firm in Vennesla.

The project team members came from different parts of Norway, with the architects located in Stavanger on the west coast of Norway, the consulting engineers and the contractor located in Agder, and the manufacturers located in east Norway. The level of BIM deployment varied among the members of the project team. While several actors worked based on 2D CAD (i.e. fire-protection engineer, main contractor, glue-lime builder, client), others used BIM technology internally (massive-wood contractor), and some collaborated based on replica files of their models. The design team (architect, consultants, and client) met on a bi-weekly basis at the consultant's premises in Kristiansand, Agder. At these meetings, they exchanged design information by using replica files of their digital models. Moreover, they conducted virtual walkthroughs through the then-combined models to discuss design issues.

3.2.3 Case C: The hospital project. Undertaking two case studies in the local wood-based building industry enabled me to identify various barriers to BIM deployment. To understand how these barriers could be overcome, I needed a case of advanced BIM practice. Finding cases of advanced BIM practice in the wood-based building industry proved to be difficult. After having consulted with the Agder county officials and several wood-based building industry experts, it became clear that I would need to look for candidate cases elsewhere. To identify a case in which designers succeeded in collaborative BIM deployment, I broadened my focus beyond the local wood-based building industry to consider cases in which timber was not used as the main building material. In early 2013, at the beginning of the third year of my doctoral project, I approached the educational director of BuildingSMART© Norway, an industry-led organization concerned with the development and implementation of ICT solutions for the building industry. By working at the forefront of BIM technology development, this person had knowledge about the status quo of BIM use in the Norwegian building industry. He suggested the new hospital project in Moss as an example of "leading-edge" BIM practice in Norway. He even considered this case as the most advanced BIM project currently being undertaken in Norway. Through his contacts, he provided me with access to this case.

The setting of Case B was the construction of a major hospital in Moss located approximately 100 kilometers southeast of Oslo. The project was initiated by the Southern and Eastern Norway Regional Health Authority (Helse Sør-Øst). The project comprised the construction of several facilities including buildings for emergencies, surgery, intensive care, patient rooms, psychiatric care, and for services such as laundry and central sterilization (Figure 3-1c and f). Altogether, the hospital buildings comprise a gross floor area (GFA) of 85.082 square meters, making it the largest ongoing construction project in the Østfold region of Norway.

The drawings were prepared by roughly 100 architectural consultants working for 3 different firms, and 100 consulting engineers. The design team consisted of a blend of Norwegian, Danish, and Swedish firms and people. While the majority of architects and the client's construction management team worked co-located in Moss, the consulting engineers were geographically distributed all over Norway. The use of BIM was prioritized in this project and supported by funding from the Norwegian government to drive the knowledge of BIM technology and deployment in the Norwegian building industry. The design team succeeded in jointly creating a highly detailed, semantically rich virtual representation of the building. The design team had established a server architecture linking all BIM workstations and enabling a "live" collaboration by the design team. The BIM-based work "spiraled" between the project team members and the model was developed and enhanced collaboratively. Table 3-2 presents the key characteristics of all three projects, the deployed BIM design systems, and the production systems used.

Table 3-2 *Key Characteristics of (1) the Case Projects and (2) the Design and Production Systems*

Key Character-istics	**Case A: Residential Project**	**Case B: Library Project**	**Case C: Hospital Project**
(1) Project			
Material	Wood-based	Wood-based	Diverse
Architectural features	One hundred apartment units	Public library, café, meeting places, and administrative areas	Public hospital, buildings for emergencies, surgery and intensive care, patient rooms, psychiatric care, service building for laundry and central sterilization
Type of production	Serial production of architectural elements, with repeated wall shapes; less labor intensive, high automation, prefabricated modular building elements	One-of-a-kind production, labor intensive, low automation, prefabrication of single wooden components, a large degree of on-site assembly	One-of-a-kind production, labor intensive, low degree of automation, large degree of on-site assembly
Project complexity	More or less "industry standard" design with a limited number of varied elements	Ambitious design of gradually shifting shapes resembling hybrid structures, numerous varied elements	Complicated and complex technical installations
Distribution of project team	Several locations in Norway and Switzerland	Several locations in Norway	Several locations in Norway, Denmark, and Sweden
(2) Design (BIM) and production (CNC) systems			
BIM capabilities	Software deployed within organizations to create single disciplinary models	Some organizations collaborate by exchanging models based on IFC files	Organizations create joint semantically rich BIM models
BIM applications	Autodesk Revit® Architecture, MEP, and Structure; ProgmanOY© MagiCAD; Cadwork®wood	ArchiCAD™; Autodesk Revit®Structure; ProgmanOY©MagiCAD; HSBCad®; Solibri™	Autodesk Revit® Architecture, MEP, and Structure; Autodesk ®Civil; Solibri™; Autodesk® Navisworks®; Byggweb®
CNC use	Robotic milling machines (Hundegger®)	Robotic milling machines (Hundegger®)	N/A

3.3 Connecting the Cases

Combining the findings of all three cases provides a solid foundation for answering the research questions raised in Chapter 1. As mentioned earlier, multiple case studies are useful for studying BIM deployment in differing contexts. However, to exploit the potential of this research strategy, the findings of the case studies need to be compared in a meaningful way. How the Cases A, B, and C have been connected in this study is presented in what follows. Figure 3-2 presents the multiple case study design applied in this thesis.

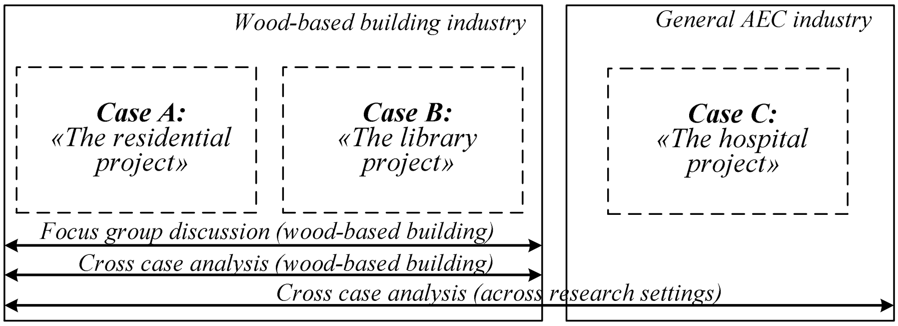


Figure 3-2. The multiple case study design.

As can be seen in Figure 3-2, Cases A and B have been chosen as representative examples of BIM-based work in the wood-based building industry. In both projects, the main building material used for the structural elements (i.e. walls, ceilings, roofs, and columns) and the outer and inner cladding was timber (i.e. the outer and inner surfaces). Cases A and B were chosen to facilitate the assessment of the current state of BIM deployment in the wood-based building industry (SQ1). Moreover, these cases were selected to answer the research question related to identifying adoption barriers emerging in BIM-based work in wood-based building (SQ2).

Conducting two case studies in the wood-based building industry (Cases A and B) allowed for comparative cross-case analysis. Identifying the differences and commonalities in BIM deployment helped to determine whether the experiences were typical for the wood-based industry or whether they depended upon the project characteristics such as complexity. The theoretical perspectives applied were configuration analysis (Case A) and cooperative capabilities (Cases A and B). A focus group (see Section 3.4) served as a venue to discuss and reflect upon the findings obtained in Cases A and B with a panel of BIM subject-matter experts who specialized in wood-based building. These experts provided their opinions of how current practice could be improved (SQ3).

As shown in Figure 3-2, Case C was a case of BIM use in the general AEC industry. It was chosen for the high level of sophistication with which the project design team operated based on BIM. This case was selected to develop an understanding of what it would take for the wood-based building industry to achieve similar levels of sophistication in their use of BIM, and thereby contribute to answering SQ3. The theoretical perspective deployed in this case was DOI theory. Comparing the findings of the empirical work in the wood-based building industry (Cases A and B) and the findings from the “extreme” BIM case (Case C) allowed for answering the overall research question asked in this thesis; namely, how can building information modeling support integrated practice in the wood-based building industry? Conducting the individual case studies A, B, and C, and the cross-case studies between A and B resulted in five publications. All findings and contributions from these papers are presented in this thesis. The overarching cross-case comparison of all cases (A, B, and C) and thereby answering the main research question, takes place in the discussion part of the thesis (Chapter 5).

3.4 Data Collection

Data collection needs to be carefully planned to ensure that the data is valuable and serves the purpose of the inquiry. The sampling and data collection techniques applied in this thesis are presented in the following. The choices made concerning the practical data collection are consistent with the underlying interpretive research perspective of this thesis. Collecting rich data affording an in-depth understanding of the interpretations of the people involved in this study was important to allow for genuine reflection. The data collection techniques applied in this project were interviews, focus groups, and, to a lesser extent, document analysis.

3.4.1 Interviews. The main technique for data collection applied in this thesis was interviews. Interviews in interpretive research serve as a way to access the interpretations of informants in the field (Walsham, 2006). The interviews conducted were directed at practitioners working at various levels in the firms participating in the case construction projects (i.e. client, architect, structural-, electrical-, and mechanical consultants, contractors, and, where applicable, the woodwork specialists). Interesting candidates for the interviews were, depending on their availability, the firms’ BIM managers, the relevant project managers, and the designers working hands-on with the technology. Their professional work had either to involve responsibility for the firm’s communication practices or an active participation in these aspects. In the three cases, 27 interviews with professionals in BIM-based work were conducted. The interviewees' professional roles and functions are presented in Table 3-3. Most interviews were conducted face-to-face, but in a few instances where this was not possible, the videoconferencing system Skype was used instead. Interview durations ranged from a minimum of 30 minutes to 3 hours. The interviews were voice recorded, transcribed, and analyzed by using the qualitative data-analysis software NVivo 9.

Table 3-3 *Roles and Functions of the Interviewees in Cases A, B, and C*

Disciplines/ Groups	**Interviewees' Profession and Function (in parenthesis)**		
	Case A	**Case B**	**Case C**
Clients	Client representative (CEO)	Client representative (technical execution)	Client representative #1 (strategic BIM manager) Client representative #2 (technical BIM manager)
Architects	Architect (design responsible)	Architect (design responsible)	Architect #1 (disciplinary BIM manager) Architect #2 (façade designer)
Engineering consultants	Structural engineer (BIM coordinator of all engineering disciplines) Geotechnical engineer (terrain modeling) Fire-protection engineer (fire simulations)	Structural engineer (BIM coordinator of all engineering disciplines) Structural engineer (structural design) Electrical engineer (electrical design) Fire-protection engineer (fire simulations)	Structural engineer (BIM coordinator of all engineering disciplines) Electrical engineer #1 (BIM coordinator electrical) Electrical engineer #2 (BIM coordinator of all engineering disciplines) Mechanical engineer (BIM coordinator HAVC)
Woodwork specialists	Timber-frame builder (CEO) Timber-frame builder (chief design engineer) Timber-frame builder (design engineer) Timber-frame builder (production manager) Structural engineer (structural wood design)	Massive-wood builder (chief design engineer) Glue-lime builder (chief design engineer) Main contractor/assembly (project manager)	N/A
Interviews	10	9	8
Data collection	September 2011– March 2012	September 2011–May 2012	April 2013

The approach to interviewing was semi-structured, which had the advantage that new ideas could be brought up during the interview. Nonetheless, the applied theoretical lenses (configuration analysis, cooperative capabilities, and DOI) guided the design of the interview guides. The questions were worded in a broad, open-ended way to allow interviewees to express their opinions on the topic freely. This type of question was deemed appropriate, since the intention of the thesis was to derive an in-depth insight from the cases. The guides were adapted for the different professional roles filled by the interviewees, meaning that the questions were phrased differently depending on whether the person interviewed was an architect or worked as an engineering consultant. To illustrate how the theory was connected to the interview guides, I present an example below; more examples can be found in Appendix A.

Table 3-4 *Operationalization of Theory in an Interview Guide (Example)*

Configuration Analysis Element	Interview Guide 'Case A' (Excerpt)
ORGANIZING VISION • Conveys a cognitive model of how the IOIS helps to organize better inter-organizational structures and processes	COMMON AGREEMENTS AND RULES • Are there some "unwritten or written data-exchange" rules regulating how information is exchanged? • Is there a common understanding of who delivers what information in what format at what time in the project? • Does your firm have certain organizational standards or guidelines for communication with others?

3.4.2 Focus groups. A useful data collection technique to understand "usage or managerial issues related to technology, systems, and IT management" is focus groups (Belanger, 2012, p. 129). This is a research method devoted to data collection based on group interactions and a topic determined by the researcher (Morgan, 1996). This technique has the advantage of allowing for discussions where the discussants query each other and explain themselves to each other (ibid.). One can distinguish focus groups from other forms of group interviews in that they are conducted with a group of 3 to 10 strangers (Morgan, 1996).

In November 2012, I conducted an industry workshop with a group of practitioners working in the wood-based building industry in the Agder region of Norway. A focus group was used in this workshop as an instrument for validation and reflections on the findings from Cases A and B. The participants of the focus group were experts in the topic area of BIM use in the wood-based building industry. Firms affiliated with the regional Agder Wood initiative were invited to send their BIM experts. Three of the invited firms responded and sent one or more representatives to participate in the workshop. The group comprised two architects, one civil engineer, and a contractor, all of whom had considerable experience in wood-based construction. In addition, these experts all had strong knowledge on design based on BIM technology. The architects had worked with modeling technology since 2007, the engineer had had BIM experience since 2003, and the timber-frame contractor had worked with modeling technology since 1998. All of the participants worked more or less on a comparable career level as they all held senior design positions in their firms. This allowed for open discussions with relatively equal participation by all involved. With four participants, the focus group was within the recommended group size (Morgan, 1996). The discussion went on for three hours. The session was voice recorded, transcribed, and analyzed by using the qualitative data-analysis software NVivo 9.

3.4.3 Document analysis. Documents were used as a supplementary source for understanding the projects and the organizations involved, and for preparing the interviews. For example, studying the documents helped in identifying key players in a project, and in developing an initial understanding of the services provided by the firms involved in a project. Examples of the documents used were trade press articles, organization charts, brochures, and newsletters. Most documents were obtained from firms' web presentations and web sources such as bygg.no and treteknisk.no, which report on recent developments in the Norwegian wood-based building industry.

3.5 Data Analysis

Interviews and focus groups were the main data collection techniques applied in this thesis. Thus, the raw data that needed to be analyzed were voice recordings of the interviews and focus group discussions, and my own written field notes. Verbatim transcripts of the recordings were produced and uploaded to the qualitative data-analysis software NVivo 9. A criterion for good research work is appropriate "sensemaking" of the data acquired. Making sense of data requires respecting its complexity, using it straightforwardly, as simply as possible, and making it widely applicable (Weick, 1979). What is believed to be possible by interpreting qualitative data is to arrive at an understanding of the bits and pieces of the social reality as experienced by the interviewees (Myers, 1994). The following work procedure was followed to analyze data:

- Recording all field data and writing it down to produce a textual account of the interviewing and focus-group experience;
- Uploading full-text transcriptions to the qualitative data-analysis software NVivo 9 to organize them in an orderly fashion and build a case study database;
- Reading and analyzing the acquired material sentence-by-sentence to reflect upon what has been said;
- Creating thematic *nodes* based on the concepts and models applied in the design of the interview guides (e.g. Table 3-5);
- Creating *nodes* while reading to capture interesting notions not covered by the concepts and models applied;
- Coding all textual accounts by assigning nodes to notions which could be related to the concepts and models applied or which were simply considered as interesting findings;
- Developing overview reports showing all text fragments assigned to a specific node;
- Exploring similarities and differences between the various data sources and making "sense" of them;
- Writing up initial findings and discussing them with colleagues; and
- Conducting member checks with interviewees.

Transcribing, reading, and analyzing the data sentence-by-sentence allowed for a close examination of the data and provided a faithful account of what had been said. An advantage of transcribed data is that it is possible to return to the text later to conduct a new analysis (Walsham, 2006). Moreover, full-text transcriptions allow for “picking out” quotes while coding and writing up the findings (ibid.). Building a case study database insured that all acquired data was kept in an orderly fashion. I conducted the coding work guided by nodes derived from the theory, as well as by applying an open coding strategy in which I assigned nodes to interesting and relevant notions identified when reading the text. This approach allowed me not only to see what the theory suggests, but also to keep some openness toward any new findings. An example of a memorable quote was the following statement made by the structural engineer interviewed in Case C:

> We get paid by the hour so if we buy software to save time then it is the client that benefits by it. Because we have to use our money to buy the software and we get less money from the client. But the client will benefit from us using less time.

This quote was interesting because it explains the behavior of organizations in BIM deployment beyond that which has been suggested by diffusion of innovation theory. However, the main coding strategy applied to comprehend the meaning of the textual data was thematic coding based on the concepts and models provided by theory (Miles & Huberman, 1999). As stated in Chapter 2, the three theoretical concepts informing the analysis were configuration analysis, cooperative capabilities, and DOI. An example of the practical coding work based on the theoretical perspectives can be found below and a more comprehensive overview of the coding work is presented in Appendix B.

Table 3-5 *Example of Coding Work Conducted in Case A*

Interview Excerpt: Fire-protection Engineer	**Codes and Notes Assigned**
Merschbrock: *Are there some unwritten or written data-exchange rules regulating how information is exchanged?* Engineer: *I have been in projects with much more control, and with much less control and I have to say that it should not be too demanding and there <u>should not be too many rules</u>. But in …* [this project] *<u>we would have benefited from a clearer understanding of how to interact</u>.*	CODES: Configuration element “organizing vision” NOTES: There is potential for being more explicit in defining how to interact based on BIM in design Argues for a “balanced” approach for establishing rules for design collaboration (tight vs. loose control) Many rules and regulations are perceived as demanding

3.6 Quality Criteria

Various threats exist regarding the quality of interpretive research work. One of the main threats for interpretive research is, as Miles and Huberman (1994) put it, "self-delusion [and], the presentation of unreliable or invalid conclusions to scientific or policy making audiences" (p. 2). Evaluation of the research design forms an important part in disciplined inquiry and ensures that the quality of a study can be judged by its audience. This section presents, based on the evaluation frameworks of Klein and Myers (1999), and Guba and Lincoln (2001), how some commonly experienced threats for interpretive work have been mitigated in this thesis. As the classical research evaluation criteria of validity, reliability, and generalizability (Yin, 2009) build on the ontological and epistemological assumptions of positivism, interpretive researchers have suggested that evaluation criteria for qualitative research instead need to claim legitimacy and trustworthiness to ensure that the attained interpretations are meaningful. Klein and Myers (1999) have suggested that the validity of interpretive research can be evaluated by scrutinizing how the hermeneutic cycle has been followed to develop one's interpretations. They suggest seven principles for the evaluation of case study research: the hermeneutic cycle, contextualization, interaction between the researcher(s) and the subjects, abstraction and generalization, dialogical reasoning, multiple interpretations, and suspicion. The following paragraph briefly presents how Klein and Myers's (1999) criteria have been addressed in my work.

This research follows the *hermeneutic cycle* by building an understanding of the entire BIM-based collaboration, based on its parts, which are the interpretations of individual interviewees. The investigation of whether and how a research *context* (i.e. the type of construction project) influenced BIM-based collaboration was an important part of this inquiry. Accordingly, the important characteristics of each project have been presented in depth. Due to my role as an outside observer, the *interaction* between me as a researcher and the individuals in the field has been limited to the few occasions during which I interviewed them. This approach had both advantages and disadvantages for the study (see the discussion on my role as researcher in Section 3-1). I have *abstracted* the findings obtained by ingraining my analytical work in the conceptual frameworks presented Chapter 2. In my articles, I have used data straightforwardly by frequently using citations derived from recorded and transcribed data so that readers are able to assess and *generalize from* my work. To prevent contradictions between theoretical preconceptions and the actual findings, I have *discussed* my findings with various people to learn about their interpretations of my work (i.e. UiA colleagues, readers, and reviewers). Additionally, I informed my work through attaining *multiple interpretations* provided by others to whom I presented my research, including fellow scholars in IS, CI, and construction management (i.e. at conferences and workshops).

A widely used evaluation framework for interpretive IS research has been proposed by Guba and Lincoln (2001). The evaluation criteria suggested by Guba and Lincoln (2001) are (1) credibility, (2) transferability, (3) dependability, and (4) confirmability. In the following, I present how the authors have defined each criterion and how I have addressed these quality criteria in my work. Table 3-6 presents an overview of the measures undertaken to ensure the quality of the thesis.

Table 3-6 *Evaluating the Quality of the Research*

Criteria	Goal	Tactics
(1) Credibility	Establishing the match between the constructed realities of respondents (or stakeholders) and those realities presented by the evaluator	✓ Multiple data sources (interviews, focus groups, and documents) ✓ Member check with key informants ✓ Discussion of the findings of Cases A and B with a group of BIM subject-matter experts in the wood-based building industry ✓ Discussing the work with construction practitioners at industry congresses such as the two BuildingSMART© congresses in Oslo (2011, 2013) ✓ Making the data available for peer review by researchers knowledgeable in the topic area of BIM in construction (by presenting parts of this work at peer-reviewed construction management, construction informatics, and information systems conferences and in the relevant journals) ✓ Presenting and discussing early stage work with external IS researchers at IRIS 2011 or at the PhD days in Oslo 2012 ✓ Discussing my work internally with my colleagues at the department including several presentations at PhD seminars ✓ The researcher himself is a subject-matter expert and had an in-depth understanding of construction work and BIM technology (by working for six years in the construction industry)
(2) Transferability	Presenting a sufficiently detailed account of the findings to allow for a reader to judge how the findings can be transferred to other settings	✓ Thorough description of the research context, the construction projects, technology, people, and their interaction ✓ Purposeful case-sampling strategy with two representative cases for projects executed in the wood-based building industry and one "extreme" case of advanced BIM use
(3) Dependability	Ensuring that methodological changes and the interpretive process are documented so that a reader can follow the choices made by the researcher	✓ Documentation of all data collected ✓ Case study database in NVivo ✓ Intensive use of direct quotations in the textual accounts of my findings ✓ Thorough description of the research process (methodology, the researcher's role, clarification of assumptions, etc.)
(4) Confirmability	Ensuring that the data and interpretations of the researcher are grounded in the context and are not just a result of the researcher's imagination	✓ Use of theory in the case studies ✓ Role of an outside observer helped to interpret the findings in a less biased manner ✓ Making the research process explicit to colleagues at UiA

(1) *Credibility*. By credibility, Guba and Lincoln (2009) refer to the necessity of ensuring that there is a match between the constructed realities of respondents and/or stakeholders and those realities presented by the researcher and attributed to the stakeholders. In other words, are the findings of a study considered accurate by the researcher, the participants, and the readers of an account? To ensure that the findings of

my work were credible, I used several data sources or triangulation (e.g. interviews, focus groups, and documents). Moreover, descriptions and explanations derived from the data were taken back to key informants in the field to determine if they were accurate accounts of what took place (Bygstad & Munkvold, 2011). In addition, I arranged a workshop with a group of subject-matter experts to discuss the findings made in Cases A and B, and, according to these experienced "stakeholders," the findings were credible and similar to their own experiences. Moreover, the results of my work have been published at international conferences and in journals, and by subjecting my work to a peer-review process, I ensured that the findings were considered credible enough for scientific publication. I have published my work in three different academic disciplines namely, IS, CI, and construction management. Not only have I discussed my work with researchers, but also with practitioners at industry summits such as the BuildingSMART® seminars (2011, 2013) in Oslo. In addition, while making sense of my data, I have benefited from helpful advice and suggestions from my colleagues at UiA and elsewhere. Once the initial findings and ideas had been derived from the data, I wrote them up, and I presented an early draft manuscript at PhD meetings in my department, at the IRIS (Information Systems Research in Scandinavia) workshop, and at the PhD days at the University of Oslo. Moreover, my prior experience from working as a civil engineer in the construction industry and my involvement in a variety of small and large construction projects helped me to understand the experienced realities better.

(2) *Transferability*. The term *transferability* refers to the process of ensuring that the findings of a study are useful beyond the study itself (Guba & Lincoln, 2009). Transferability has been accomplished by presenting the findings in a way in which readers are able to judge how the findings may be useful in a different context. I made the research context, the technology used, the people involved, and their interactions explicit. The results of my work have been published, after peer review, by different research communities. Moreover, the many discussions with practitioners and scholars about my work and its findings made me confident that practitioners would find this work interesting and applicable for their context.

(3) *Dependability*. It is important for the quality of interpretive research to document in a plausible way how a researcher arrives at his/her interpretations. In this study, the research process is made explicit to allow others to follow how I arrived at my interpretations and conclusions, and what has changed over time. The first step to documenting the process of research is maintaining an overview over all of the data and literature collected throughout the study. This has been accomplished by creating and

maintaining a case study database in NVivo and a literature database in Endnote. To allow others to follow my interpretations, I have clarified my research strategy, my role as a researcher in this study, and I have clarified my assumptions.

(4) *Confirmability.* A criterion ensuring that the interpretations of the researcher are rooted in reality and are not a result of his/her imagination is to make the research confirmable. One strategy for ensuring confirmability is in making the data available, and describing the logic used to move from the data to the final results. In my writings, I have made explicit how I arrived at my conclusions by explicating the research approach and by presenting data in depth to ensure that the reader will be able to follow how I arrived at my conclusions. My advisor participated in some of the interviews and the focus group discussion, making him an informed discussion partner while analyzing and reflecting upon these aspects. Learning how my advisor viewed some of the issues emerging in my work and discussing our interpretations helped me gain confidence in my findings. Moreover, I have continuously debated my work in progress with my colleagues at UiA. I argue that these measures helped me to control for any potential bias in my interpretations. Moreover, the data collection and analysis of my case studies has been guided by theory, which served as a "common thread" running throughout my sensemaking process. Furthermore, recording and transcribing all of my data helped me to root my interpretations in what has actually been stated by the interviewees. Last, positioning myself as an outside observer helped me to maintain a balanced view on the phenomenon under study.

3.7 Ethical Considerations

There might be confidentiality and privacy issues arising, as the interviews might have negative consequences for the people participating in the study. My study was, among other things, concerned with work practices, the capabilities of people, and how well they operated in teams. Answering such questions honestly can be a delicate matter, especially when considering that future, potential customers might read how design work in a project did not function well. Individual designers might face negative consequences when answering such questions honestly. Therefore, the data collection was conducted in a transparent manner, meaning that participants were made aware that they were participating in a research project. Before embarking on the interviews and the focus group discussion, informed consent was sought and interviewees were informed that data would be collected and used in research. Further, anonymity was offered to both the firms and individuals participating in the case projects. According to Walsham (2006), it is important to mention a problem regarding confidentiality: even though anonymity is granted both sponsors and senior personnel might be able to take a good guess at who is being discussed and/or who the interviewee is.

4 Results

Addressing the research questions raised in Chapter 1 resulted in six publications presented in international journals and at international conferences. Table 4-1 contains a list of the articles arranged in the order in which they have been written. Full-text versions of the articles can be found in Appendix C. The interdisciplinary nature of my inquiry is mirrored by the choice of publication outlets. While the main focus of my work was to contribute to the emerging discourse on BIM in the IS literature (ref. Publications 1, 3, 4, and 6 in Table 4-1), construction-specific outlets have also been targeted (Publications 2 and 5). This strategy ensured that the results of my work were not only considered relevant by IS scholars, but also by construction experts.

Table 4-1 *Research Publications*

1. Merschbrock, C., & Munkvold, B. E. (2012). A research review on building information modeling in construction: An area ripe for IS research. *Communications of the Association for Information Systems (CAIS),* 31, article 10, 206–229.
2. Merschbrock, C. (2012). Unorchestrated symphony: The case of inter-organizational collaboration in digital construction design. *Journal of Information Technology in Construction (ITcon*), 17, article 22, 333–350.
3. Merschbrock, C., & Munkvold, B. E. (in press). How is building information modeling influenced by project complexity? A cross-case analysis of e-collaboration performance in building construction. *International Journal of E-Collaboration (IJeC).*
4. Merschbrock, C., & Wahid, F. (2013). Actors' freedom of enactment in a loosely coupled system: The use of building information modeling in construction projects. *Proceedings of the 21st European Conference on Information Systems (ECIS 2013),* Paper 124, Utrecht, The Netherlands, 5–8 June.
5. Merschbrock, C., & Munkvold, B. E. (2013). Improving inter-organizational design practices in the wood-based building industry. *Proceedings of the 7th Nordic Conference on Construction Economics and Organisation*, pp. 479–489, Trondheim, Norway, 12–14 June.
6. Merschbrock, C., & Munkvold, B. E. (2014). Succeeding with building information modeling: A case study of BIM diffusion in a healthcare construction project. *Proceedings of the 47th Hawaii International Conference on System Sciences(HICSS 2014),* pp. 3959-3968, Big Island, Hawaii, 6–9 January.

Paper 1 is a review article synthesizing the literature on BIM in construction and thereby establishing the foundation for the research work presented in this thesis. The following three papers were based on fieldwork in the wood-based building industry (Cases A and B), while paper 5 reports on the focus group discussion with industry experts. Paper 6 is based on a study of BIM-based design in the general AEC industry (Case C). Table 4-2 presents an overview of the research questions that were focused in each article. The overall research question of this thesis "how can building information modeling support integrated practice in the wood-based building industry?" is answered in

Chapter 6 based on the results presented in the individual publications. In this chapter, the publications are presented and briefly summarized.

Table 4-2 *The Relationship between Research Questions and Publications*

Research Questions		Publications
SQ1	What is the current state of BIM adoption for integration in the wood-based building industry?	1,2,3,4
SQ2	What are the predominant social, environmental, and technical barriers for the adoption of BIM in this industry?	1,2,3,4
SQ3	What changes will be required with respect to work processes and interaction between the actors in the industry to achieve improved design information sharing through the use of BIM?	1,5,6

4.1 Paper 1: A Research Review on Building Information Modeling in Construction

Focus. The article comprises a review of 264 journal articles published on BIM-related topics before January 2011 (the cut-off date of the review). The framework that was applied to support the classification of the articles was Turk's (2007) "research themes in construction informatics." The framework provides an overview of major IT/IS-related research themes in the context of the AEC industry. The themes presented in Turk's framework have been identified based on a Delphi-study among 50 senior scholars of CI, who were asked to name what they considered as the most important areas of IS/IT research in the construction industry. Classifying BIM research based on this framework allowed for finding areas in need of further research attention, while at the same time addressing what is important for the construction industry. The article was written with the intention of identifying what could be interesting opportunities for IS researchers to contribute to the ongoing discussion.

Findings. Most of the discourse was found to take place in engineering disciplines, with CI journals such as Automation in Construction and the Journal of Information Technology in Construction being the outlets publishing most BIM-related work. Current BIM research is characterized by a strong emphasis on ICT development topics, with roughly 40% of all articles discussing how BIM's functional affordances can be improved to make it a better technology for its users. In addition, the deployment of BIM technology and its impact on organizational practice are discussed in the research. As documented in the article, many of the current research challenges related to the adoption and use of BIM in building construction have a clear resonance with focal areas in IS research. Still, this area has been largely neglected in mainstream IS research. Several limitations in the current BIM literature that represent research avenues that are worth pursuing for IS researchers have been identified in this study. The following areas are in need of further IS research: (1) studies on the relationship of BIM's functional affordance and human agency; (2) studies on the adoption and deployment of BIM for inter-organizational collaboration; (3) the influence of organizational culture on BIM use; (4) identifying the capabilities of BIM for transforming industry practice; and (5) identifying BIM's business value.

Contribution. Based on a systematic review of journal publications on BIM, this article provides an overview of the nature and scope of the research conducted in this domain to date. The article points to several limitations in current BIM literature that represent research avenues that are worth pursuing for IS researchers. Based on this, one area that is especially in need of further IS research has been focused on in this thesis; namely, the adoption and use of BIM for inter-organizational collaboration. As pointed out in the article, there is a well-established knowledge base in IS research that can be drawn upon for studying these issues (Robey et al., 2008). A more detailed account of how BIM deployment literature can be complemented by further research is provided in Chapter 2 (based on the article presented in Appendix C).

4.2 Paper 2: Unorchestrated Symphony

Focus. The setting for this article was a residential project in the wood-based building industry in the Bergen area of Norway (Case A, introduced in Chapter 3). The research was based on interviews conducted with members from the various professions involved in the design of this project. As identified in the review article, BIM scholarship to date has largely focused on the technical requirements of BIM and less on the inter-organizational practices surrounding the modeling activity. This provided the rationale for applying the "configuration analysis approach" (ref. Section 2.3) to study BIM-based work in a wood-based construction project. Doing so enabled me to develop an understanding of the extent to which the design team in this project built strategies for collaborative BIM deployment. Exploring BIM-based teamwork in a "typical" project of the wood-based building industry was considered a good start for this research project.

Findings. Applying a configuration analysis approach allowed for a structured analysis of BIM-enabled collaboration. Some organizations in the design team had prior experience in collaborative BIM-based work, whereas others were inexperienced and still worked based on 2D design technology. By conducting a configuration analysis, it has been possible to point out both leadership decisions and communication practices that were required to enable a fully functional BIM system; that is, the creation of an organizing vision, overcoming conflicting motivations, and active discussion of BIM modalities. Improvement is possible by first creating a shared organizing vision toward working together in BIM. Actors need to discuss their desired communication outcomes and the role of BIM in facilitating such communication. Second, discontinuities caused by different firm locations, languages, and technical capabilities need to be mitigated for. Design teams could, for instance, use shared IS such as videoconferencing tools and online repositories to facilitate collaborative design work surrounding the modeling work. Third, a “critical mass” of designers would need to be convinced about BIM’s business value at the inter-organizational level to make it work. In this case project, with only the one actor (the timber-frame contractor) expressing an interest in collaborative BIM work, this critical mass was not reached. Project actors would need to discuss what might be gained by deploying a fully functional BIM system. Last, several designers in the case project struggled to overcome technical challenges for BIM adoption. Technical problems resulted, for instance, from a lack of interoperability between BIM and GIS solutions and/or other advanced engineering systems.

Contribution. The article complements existing research on BIM deployment by providing insights into inter-organizational alignment and the areas in need of managerial attention when BIM is used for the integration of digital design in construction projects. As demonstrated in the article, configuration analysis provides an overview of the current state of a collaborative BIM-based effort. The organizations in the case study did not adjust their inter-organizational processes for collaborative work and operated instead as a group of “automation islands.” Configuration analysis is a useful theoretical lens with which to explicate the mechanisms bringing together the disparate organizations in BIM-mediated work. However, it lies beyond the scope of a configuration analysis to identify what leads a set of organizations to prioritize collaborative BIM-based work and what precedes the establishment of a “configured” inter-organizational work environment (this is further discussed in Section 5.2). Ergo, further research work was needed to identify what makes project teams perceive BIM-based collaboration as necessary, desirable, and important for their projects.

4.3 Paper 3: How Is Building Information Modeling Influenced by Project Complexity?

Focus. Article 3 reports on a cross-case analysis of Cases A and B. Both case projects are similar as they are timber structures executed and designed by woodwork experts. However, they differ in their complexity, with one being a more or less industry standard residential project and the other being an ambitiously designed public library. This paper is motivated by the findings made in article 2. As stated above, only one firm perceived collaborative BIM-based work as necessary for designing the residential project. My interest in this paper was to investigate whether this perception changes once a project becomes more complex. Complexity is here defined as the number of varied elements of which a building is constituted. The idea was to compare collaborative BIM-based performance as displayed by two project teams working in projects of differing complexity (Cases A and B). As explicated in Chapter 3, a good lens for evaluating collaborative performance in construction projects is “cooperative capabilities.” The model applied for the assessment of BIM-related capabilities in this article is the Building Information Modeling Maturity Index (Succar et al., 2012). The maturity index is a staged assessment model suggesting five categories of collaborative BIM modeling capabilities. The stages range from a status in which organizations do not yet deploy BIM technology (pre-BIM) to stages where designers collaboratively create a shared BIM model (integrated project delivery). An overview of all BIM maturity classes, as suggested by Succar et al. (2012), is presented in the article (Appendix C).

Findings. It is true for both projects that several design team members had developed prior expertise in generating disciplinary BIM-based models. It is equally true for both projects that some designers did not possess the capability and technology to participate in collaborative BIM design. What differs between the projects is that in the complex project (Case B) collaborative BIM design was prioritized, whereas in the simple project (Case A) it was not considered as important. While in Case B digital models were exchanged among the design team (i.e. architect, structural, HVAC, and electrical consultants), no such practice took place in the simple project. What also appeared from the data was that increasing the level of BIM-based collaboration is costly for a design team, as it requires a significantly higher amount of planning work. Thus, the project team in Case B perceived the business value of BIM for their project as high enough to justify the additional costs required for model-based collaboration. Although team B placed more emphasis on BIM than team A, both teams were far from achieving integrated design practice. None of the teams succeeded in jointly creating BIM models, and the highest level of collaborative capability observed in the cases were exchanges of digital models based on a proprietary file format for model collision control (Case B). Applying Succar et al.'s (2012) framework allowed for categorizing the projects into BIM capability categories. The levels of BIM capabilities displayed by the project team in the simple project ranged from pre-BIM, with firms not using any BIM, to BIM stage 1, with models being created mainly for internal use. In the complex project, the BIM capability levels ranged from the pre-BIM stage, to BIM stage 1, to BIM stage 2. BIM stage 2 is achieved once organizations have developed expertise in generating disciplinary models and collaborate by exchanging digital models by interchanging proprietary formats. In Case B, some organizations collaborated by exchanging models based on the Industry Foundation Classes (IFC) file format for the purpose of conducting "visual" collision controls.

Contribution. This paper inquired into the reasons as to why and when organizations in the wood-based building industry prioritize BIM-based collaboration. The findings of the paper show that the intensity of BIM-based collaboration is influenced by project complexity. Our analysis documents how designers engage in collaborative BIM design only if they perceive that there is a clear business value in doing so. Even firms with sophisticated BIM capabilities and knowledge of collaboration remain hesitant in engaging in digital BIM-based collaborative work when the immediate business value of such collaboration is not evident. This paper has provided an initial conceptualization of the relationship between design productivity, project complexity, and BIM-based collaboration.

4.4 Paper 4: Actors' Freedom of Enactment in a Loosely Coupled System

Focus. Article 4 is a conceptual paper that builds on the findings reported in articles 2 and 3. It is true for both projects that even if collaborative BIM-based design took place, the specialists delivering the wooden components remained largely excluded from it. One reason for this was that they joined the project teams quite late due to the design–bid–build procurement strategy applied by the clients. Joining late reduced their opportunity for engaging in collaborative design. The manufacturers in both case projects claimed that by not having the opportunity to partake significantly in the design phase, their ability to utilize their BIM systems and CNC machinery to the fullest was reduced. Naturally, these firms were in need of detailed, parametric 3D design data to maximize the utility of their CNC machinery. The idea presented in this paper was to develop a better understanding of why some project members (e.g. manufacturers and contractors) perceive that they have fewer opportunities to partake in collaborative design than others do (e.g. architects).

Findings. It became clear that the vision of creating "digital fabrication environments" will remain a utopia unless manufacturers are provided with the opportunity to engage in collaborative BIM-based work. Using architectural and engineering design data straightforwardly in production would require: (1) developing a project-level IS/IT strategy channeling the data flow efficiently to the persons producing machine-readable data, (2) applying a procurement strategy in which the entire project team are able to participate in BIM-based collaboration, and (3) creating a "project-wide" awareness of which information is required by whom, when, and in which format. The conceptual framework advanced in this paper is derived from the extant literature on project-based work, and by explaining patterns observed in collaborative BIM-based work in case projects A and B. The degree to which an organization is "free" to deploy BIM (which in the paper is termed as *freedom of enactment*) is conceptualized to depend upon the degree of task and technology interdependence (e.g. the contractors need accurate 3D parametric data delivered in a file format that is interoperable with local BIM solutions), the degree of coupling (e.g. loosely coupled project teams are focused on short-term productivity while hampering innovation), and an actor's position in the process chain (e.g. the wood contractors joined relatively late in both projects). "Constituted enactment" can be seen as the condition in which an actor turns his/her potential to use BIM technology into actual deployment. "Conversion factors" are the enablers required for the transition from freedom of enactment to constituted enactment. Further details of how the conceptual model has been built are presented in depth in the article (Appendix C). The conceptual model is presented in Figure 4-1 below.

Contribution. The conceptual model provides new insights to understand the antecedents of BIM deployment and offers a possible explanation for why it is so hard for the manufacturers to utilize their BIM and CNC technology. Based on empirical data, it was conceptualized how actors' positions in the process chain, task and technology interdependence, and the degree of coupling among the organizations partaking in a construction project all influence the extent to which a firm can deploy

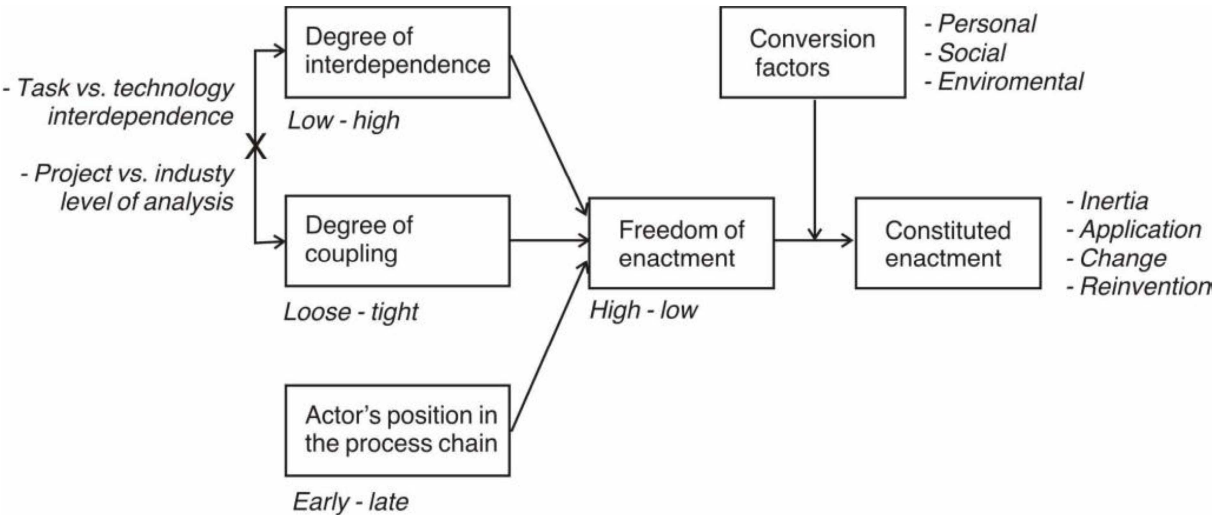


Figure 4-1. Conceptual model of the freedom of enactment (Merschbrock & Wahid, 2013/Appendix C).

BIM to the fullest. The study also has implications for practice. It provides insights for practitioners for developing better policies in their projects allowing for collaborative BIM deployment. Moreover, the presented model is useful for increasing the awareness of the actors involved in the early stages of the projects in terms of them considering the possible problems that they might inflict upon others by the inappropriate or careless use of BIM systems. For instance, when designers early on in a project decide on using BIM predominantly internally to create disciplinary models, and at the same time do not commit resources for a rigorous collision control, there is a likelihood that these models will be misaligned. While this practice may seem convenient and less costly for designers in the early project stages, it will inflict problems upon manufacturers once the digital work is handed over.

4.5 Paper 5: Improving Inter-organizational Design Practices in the Wood-based Building Industry

Focus. This article reports on a focus group discussion with a panel of industry experts working with BIM in the wood-based building industry. The panel was comprised of two architects, a structural engineer, and a timber-frame manufacturer from the Agder region of Norway. The motivation for conducting the focus group discussion was twofold. First, I wanted to understand if the findings of case studies A and B were in line with what others in the industry experience as well. Second, the discussion provided an opportunity for developing ideas on how challenges in current BIM-based work could be overcome. More details on the modalities of the focus group discussion can be found in Chapter 3. The issues raised by the workshop participants were classified into topic areas based on the “3D working method”, which is a framework offering a conceptualization of the activities that are required to create, exchange, and re-use the modeling data (bips, 2007).

Findings. The focus group discussed ideas for a managerial response to the currently experienced issues in BIM-based design. What became apparent from the discussion was that many manufacturers operating in the wood-based building industry have invested heavily in new CNC machinery and BIM software. However, the current use of this machinery is limited to the production of simple timber-based building components such as trusses and frames not requiring intensive 3D modeling efforts. The discussants pointed out that several firms are exploring the possibilities for producing more advanced architectural components. However, making available the necessary machine-readable 3D data for the drafters creating the CNC files does not receive priority in many projects. This has been attributed to a lack of BIM-based collaboration in the design teams. According to the discussants, the main barriers for collaborative BIM deployment were low organizational BIM capability, late involvement of manufacturers in projects, designers continuing to work based on 2D CAD, ill-defined data-exchange processes, and a lack of demand and prioritization from clients for including BIM in the project cost and schedule.

The barriers mentioned in the discussion were in line with those identified in case studies A and B reported above. The following changes were perceived as necessary by the discussants for improving current practice: (1) establishing discussion forums in which knowledge about BIM could be disseminated, (2) establishing criteria for a structured model exchange, (3) challenging the information flow toward the designers creating CNC data, (4) defining interfaces and the scope of disciplinary design contributions, (5) supporting novel and non-users of BIM in the project’s design, (6) BIM startup meetings in which everybody participates, (7) establishment of a quality system for model quality assessment, (8) precisely formulated BIM contracts, (9) early involvement of timber-frame manufacturers, (10) finalizing design before construction, (11) additional financial resources for design, (12) getting the client’s buy-in for BIM, (13) managerial attention on BIM collaboration, (14) design decisions would need to be frontloaded.

Contribution. Especially the absence of a stable information flow from the early design phase to the code generator creating the machine-readable files appears to be a problem that remains difficult to overcome for practitioners in the wood-based building industry. However, some important managerial responses that could prove useful in mitigating against the currently experienced issues in collaborative BIM design in the wood-based building industry have been identified. For instance, services should be established where experienced BIM users aid less experienced collaboration partners in creating digital models; guidelines for inter-organizational BIM-based design should be customized for the needs of the wood-based building industry; the role of a central BIM manager serving as a project "communication hub" should be established; knowledge on the application of BIM and CNC technology in wood-based building projects should be disseminated to clients and practitioners; and the information flow would need to be channeled to those designers producing the CNC data.

4.6 Paper 6: Succeeding with Building Information Modeling

Focus. The setting for this article is a hospital construction project in Moss, Norway (Case C, introduced in Chapter 3). This case project was recommended to me by the educational director of BuildingSMART® Norway as the most advanced case of BIM use in the Norwegian construction industry. The research in this thesis has documented how many organizations in the wood-based building industry struggle with how to work with BIM. This study was undertaken to provide the wood-based building industry with a useful starting point for improving their current BIM practice. The idea in this study was to get acquainted with how the design team in the hospital project succeeded in creating a collaborative environment based on BIM. This study was based on a series of interviews with the key players responsible for arranging the BIM-based work in this project. DOI theory served as a lens guiding my analysis of the factors that are important for the sophisticated, collaborative use of BIM technology. The case study approach applied in this study allowed for putting the diffusion factors presented in prior work to the test in the empirical setting of a construction project, and for building practical and conceptual knowledge about BIM's diffusion as a collaborative system that is useful for other projects.

Findings. In this case project, the core project team worked based on one shared BIM model and others were included through the active exchange of IFC-based models. Moreover, the design team produced what the client perceived to be an acceptable virtual prototype of the buildings. By conducting a DOI-based study, it became possible to identify several inter-organizational factors driving the diffusion of BIM at the project level. The identified factors include (1) the establishment of BIM change agents championing collaborative BIM use at the project level; (2) putting into place a cloud computing infrastructure linking design systems, databases, and portals through the web; (3) appointing software developers to constantly service and change the infrastructure throughout the entire design and construction cycle; (4) establishing solid BIM contracts; (5) establishing a BIM learning environment (e.g. guidelines, manuals, taught courses); (6) placing BIM super users in each design sub-unit; and (7) establishing a BIM management structure including new roles and responsibilities. Moreover, (8) interoperability was mainly achieved by using software that was provided by the same vendor, and (9) by establishing a cross-disciplinary, model-exchange routine based on IFC files. Despite intensive BIM deployment throughout all of the design stages, this project had still been procured based on a design–bid–build strategy with entrepreneurs and designers joining the team later.

Contribution. The analysis based on DOI allowed for identifying diffusion factors aiding the designers to set up a collaborative BIM workspace. This article has provided transferable insights about the factors aiding designers in BIM design. Several areas in need of further research have been identified in the article. These include identifying the value of virtual team work for construction projects, identifying the way in which BIM diffusion is influenced by a project's context, and identifying how the content produced in BIM can be managed throughout the life-cycle of a facility. DOI theory has been used in this article in a similar way to that suggested by Lyytinen and Damsgaard (2001). To understand the dynamics of BIM innovation, I went beyond what has been suggested in the traditional DOI literature and inquired into the "local, complex, networked, and learning intensive features of technology, [and] the critical role of market making and institutional structures in shaping the diffusion arena" (Lyytinen and Damsgaard, 2001, p. 14).

5 Contributions

Chapter 5 brings together the findings of the research and provides an overview of the key implications for the wood-based building industry and the theoretical contributions of the research work. The focus of the thesis is to develop an understanding of the preconditions for integrated BIM-based design in the wood-based building industry. The current limitations in BIM-based work in this industry served as a starting point for identifying the antecedents presented in Section 5.1. Further, this work draws from and extends former research in various areas and the key theoretical implications of the thesis are presented in Section 5.2.

5.1 Key Implications for Wood-based Construction

This section summarizes the findings on BIM and digital collaboration that are considered relevant in the context of the wood-based building industry. As stated in Chapter 1, the vision of this industry is to establish "digital fabrication environments" where architectural design data can be used straightforwardly without costly redesign. In the following paragraphs, the key aspects that are important to realize these environments by deploying BIM technology are presented. First, the processes and technological aspects relevant to creating collaborative BIM design spaces are discussed. Second, the influence of project characteristics on the collaborative work is summarized. Third, how a design team's capabilities influence collaborative BIM work is elaborated. Last, I discuss how integration between design and construction could be further improved by using BIM.

5.1.1 Creating collaborative design spaces. The results of my studies indicate that many design teams in the wood-based building industry struggle to build design spaces for their collaborative BIM work, and that traditional 2D-based design processes are frequently left intact. Not adjusting the way of working to incorporate the new systems leads to an underutilization of BIM. This finding is in line with research arguing that users are likely to use new technology analogously to the old technology (Orlikowski & Gash, 1994). Many organizations operate as "automation islands" where BIM deployment is focused internally as opposed to engaging in collaborative interaction. The construction industry's prevailing focus on internal processes rather than on collaboration has been noted in earlier research (Neff et al., 2010).

Instead of working in a shared model, data is exchanged based on replica model files (IFC), full-fledged models, and conventional 2D drawing sets. According to the findings from the advanced BIM project in the hospital case, building a design space for collaborative BIM begins by agreeing on a policy for inter-organizational work, continues by building a shared information infrastructure, and concludes by allocating the resources required for collaborative work (e.g. personnel, money, and time). To transform design practice substantially and to achieve a more integrated way of working, old 2D-based design processes and infrastructure would need to be changed. The following paragraphs elaborate on how this could be achieved in the context of the wood-based building industry.

Building functional, collaborative BIM design spaces for the wood-based building industry would require teams to identify their information needs and to engineer their collaboration processes accordingly (Kolfschoten, van der Hulst, den Hengst-Bruggeling, & de Vreede, 2012). A precondition for building a functional design space is to develop a shared vision among the project team members on how to operate and organize the shared structures and processes required for BIM (Lyytinen & Damsgaard, 2011). Design teams need a common collaboration policy in which clients, designers, contractors, and manufacturers agree on the rules for their collaboration. This could be done in BIM startup meetings in which everybody participates. How a policy for BIM can be built has been demonstrated in the hospital case project where the design team negotiated aspects of the collaborative work and developed BIM manuals and handbooks that were then distributed to every BIM workstation in the project. Similar policy statements and practical guidelines, when adjusted for the information needs of the wood-based building industry, could serve as useful resources, providing the team with a “code of conduct” guiding their collaborative work. Building procedural guidance into the systems may support the appropriation of integrated design solutions such as BIM (Munkvold & Zigurs, 2006). This could take the form of features directing users in their interaction with the system and collaborative scripts supporting the team process (Briggs, deVreede, & Nunamaker, 2003).

Not only is it necessary to establish rules for collaborative working, but also the related inter-organizational processes and infrastructures need to be agreed upon and aligned. Again, the advanced hospital project provided an example of how this could be achieved. The team worked jointly on the same BIM model based on a cloud computing infrastructure. Model modifications made by team members were updated daily and automatically made available for all BIM workstations. The IS/IT infrastructure consisted of several web portals, web BIM servers, and databases all linked via wide area network (WAN) technology, allowing the team to remotely access and alter the design. Building such an advanced, cloud-based BIM infrastructure allowed for the design team to operate in a distributed manner from several locations in Norway. To enable “live” collaboration with the designers who were jointly editing a central and shared model, the design team decided to stay within the product range provided by one software vendor. Doing so allowed for tighter integration as, for example, the architectural model generated automatically changes to the structural model, and vice versa (Eastman et al., 2011). This required a range of designers replacing their legacy systems. While deploying BuildingSMART's© "open-BIM" IFC-based file-exchange approach would have allowed designers to keep their systems in place, it would not have enabled synchronous digital collaboration to a similar extent.

Specially trained BIM personnel would be required to maintain and operate the design space. These professionals would need to have an IT/IS background and a thorough understanding of systems development, implementation, hardware updates, maintenance, and IS training. For instance, the complex IT infrastructure consisting of web servers, portals, and databases needs to be maintained for the project duration. Further, after having the rules, infrastructure, and processes in place, the collaboration requires close management. The design team in the hospital case project had positioned BIM managers within every group of designers and two change agents at project level. This management function served as a central BIM communications hub, taking care of the structured distribution of model-based design data at project level. Further, this management function was a control instance to enforce agreements regarding the quality, interfaces, and delivery time of disciplinary modeling contributions. BIM managers would need to be able to spot weaknesses in organizational BIM modeling practices and introduce corrective measures. This would require a powerful actor or somebody having the legitimacy required for effective management. Moreover, these persons would need to have sophisticated communication skills to be able to create an environment in which designers feel comfortable in sharing their designs. Similar ideas were brought up in the focus group discussion as a possible response to the currently experienced barriers for collaborative BIM design in the context of the wood-based building industry.

The hospital case clearly showcased how building and operating a collaborative BIM design space would be a feasible option in the context of the wood-based building industry. The designers' preexisting BIM capabilities and the information infrastructure found in the advanced project resembled those found in the wood-based building industry. As the design team in the advanced hospital project still succeeded in establishing a functional design space for BIM, it indicates that this could also be possible in the wood-based building industry. However, what needs to be considered are the costs, time, and personnel required for establishing and maintaining such an infrastructure. In the hospital project, BIM work benefited from Norwegian government funding, and similar resources are usually not available for project teams. Moreover, collaborative BIM design work in wood-based construction would need to focus more strongly on creating BIM models that are sophisticated enough for automated production, which requires the design space to be engineered for this purpose. While most of the ideas for building a design space appear to be relevant for wood-based construction, some caution is needed, as their applicability would need to be judged on a project-by-project basis, taking into account the information needs in each specific context. The large number of resources required for operating a functional inter-organizational design space for BIM may explain why design teams in wood-based construction remain hesitant in engaging in digital collaboration. An opportunity for overcoming this hesitation would be to develop the infrastructure in a way that it can be mobilized in other projects with a new configuration of actors.

5.1.2 Influence of project characteristics. It has been argued that BIM-based collaboration has positive implications for design performance in construction projects, regardless of the project size or complexity (Hore, Montague, Thomas, & Cullen, 2011; Sebastian, Haak, & Vos, 2009). Moreover, others argue that "if high levels of interaction between the participants emerge [e.g. through full BIM cooperation], companies in building projects will be likely to obtain […] higher cost benefits and less risk" (Grilo & Jardim-Goncalves, 2010, p. 530). However, in the wood-based building projects in my study, the practitioners did not perceive BIM to have unconditional positive implications for all project situations. Designers of simple projects may not want to spend time and resources on establishing a collaborative BIM space when the design can be solved without it. In other words, project teams will only embrace BIM when the perceived benefits of digital collaboration outweigh the costs associated with establishing a collaborative network. Moreover, introducing BIM in a project may lead to initial design productivity losses while the team still adjusts to the new way of working.

Clients are important actors when it comes to deciding whether collaborative BIM work is embraced in a project (Schroth & Schmidt, 2009). However, currently only a few "enlightened" clients make the most of their design team's collaborative intelligence (Owen et al., 2010). The findings from my research indicate that clients, especially when the project is simple, may be indifferent to what design technology is deployed and may be unwilling to commit additional resources for BIM use. Certainly, large property owners are aware of the benefits of BIM, but less professional, smaller building owners and clients might not be aware of the IT deployed in construction design. In the focus group discussion, it was suggested that design teams could develop two proposals when tendering for a project. One of these estimates could include intense collaboration and the related managerial tasks, and one could just include an estimate for "business as usual" standard practice. This strategic tendering approach could enable clients to choose from these solutions. Arguments to achieve a client's "buy-in" of a BIM-enabled project could, for instance, be a better ability to assess whether the proposed design solution meets the requirements, the ability to assess what the building will look like in its surroundings, benefits for operation and maintenance, better cost estimates, and a reduced fault rate (bips, 2007).

Receiving a client's buy-in for BIM by explicating the potential benefits of BIM use and adopting a more structured approach to estimate BIM's business value taking into account project complexity could improve current practice in the wood-based building industry. The advanced BIM project in the hospital case serves as an example for a client-driven BIM project. The client perceived BIM as an important means to ensure the creation of a high-quality building meeting user requirements, and to streamline the building's operation. The client promoted BIM by providing the necessary inter-organizational IT infrastructure, committing sufficient financial resources to the design stages, and by placing BIM managers in the project team. The BIM managers had the task of enforcing active and collaborative BIM use in the project. The strategy adopted to diffuse BIM in the advanced project resembled a "commanding" approach with change being driven by the client (Pries-Heje & Baskerville, 2010). This approach has been suggested as being most useful in situations where organizational change is needed rapidly, and formal structures need to be changed (ibid.). Taking a commanding approach appears promising at first sight, as it favors a rapid diffusion of BIM that is needed in projects that are pressured by time. However, it may not be the right action to perform in all project situations, since it may be resisted by project team members not perceiving BIM as important (Baskerville & Pries-Heje, 2010).

5.1.3 The project team's building information modeling capabilities. Of the 19 professionals interviewed in projects for the wood-based building industry (Cases A and B), only about half had experience of working with object-based design systems. The remaining firms continue to work based on their old, pre-BIM 2D CAD solutions. This finding corroborates research reporting that the construction industry is generally slow to adopt new technology (Gu & London, 2010). Apart from those firms simply not perceiving BIM as important, several firms reported a lack of commercially available BIM solutions covering their area of expertise (e.g. fire-protection engineers and geotechnical consultants). In terms of collaborative maturity, all firms using BIM were comfortable in using the systems in house to produce disciplinary 3D models. However, most BIM-capable actors lacked prior experience and "know-how" in BIM-based collaborative design.

When brainstorming ideas for how the wood-based building industry could overcome the current lack of BIM knowledge, the focus group suggested several potential solutions. First, it was suggested that project teams should develop an approach in which BIM-knowledgeable design team members should aid others in their digital work. Moreover, the experts all stressed that design teams would need more time than was currently available to complete their design work. Time pressure has been identified as an important barrier for successful use of inter-organizational ICT in construction projects (Adriaanse, Voordijk, & Dewulf, 2010). Moreover, the establishment of government-funded competence centers was mentioned as an option to improve BIM-related knowledge dissemination in the AEC industry (Hore et al., 2011). Competence centers having a special focus on the needs of the wood-based building industry, addressing both BIM- and CNC-related topics, could be a useful resource for current practice.

At project initiation, most designers in the hospital project did not have prior experience in BIM design and collaboration. Recognizing this, the client declared the project as a "BIM learning project", allowing companies to develop skills and processes while working on the project. Moreover, the training of the project team was carefully planned. The training was delivered based on three basic approaches: super users (internal and external), cross-disciplinary BIM training, and learning aids. Highly capable BIM designers were identified and formally appointed as "BIM super users" for their respective design groups. The cross-disciplinary BIM training was conducted based on three-hour courses developed to introduce the designers to the basic functionality of the inter-organizational systems.

Disciplinary BIM training programs were usually provided by software vendors to teach the users the skills necessary for designing based on a particular disciplinary design solution. The learning aids were developed by people having prior BIM experience from working hands-on with BIM technology within their disciplines. The learning material was customized for the unique learning requirements of each discipline. Further, software developers were appointed during the project to assist designers in overcoming technical BIM-related challenges to establish links between previously unconnected designers (e.g. fire-protection engineers). The approach taken by the project team in the hospital case project to disseminate “collaborative” BIM knowledge could serve as an inspiration and template for designers in the wood-based building industry.

5.1.4 Moving building information modeling data from design to production. The sequential nature of construction projects, where (1) architects explore aesthetical solutions, (2) consultants explore technical solutions, and (3) contractors and manufacturers build the specified product, has been identified as a root cause for poor communication resulting in costly rework and unproductive downtime (Love & Li, 2000). The actors involved in the late stages of the process chain, such as the timber-frame builders, depend on the design work produced by the architects and engineers. By joining the project later, the timber-frame builders in case studies A and B had few opportunities to actively engage in collaboration and influence the way in which the design was produced. The findings confirmed that not all project team members are able to partake in BIM collaboration and especially those working at the “periphery of digital innovation networks” are frequently excluded from innovative practices (Yoo et al., 2010).

As Scheurer (2010) puts it, “The idea of just sending a 3-D model to the fabricator and receiving a few containers full of mass-customized components some days later is downright utopian” (p. 93). Nonetheless, the timber-frame manufacturers in the case studies expected that the design made by the architects and engineers could be translated directly into the production process. In none of the projects studied did the manufacturers perceive the received modeling data to be of high practical value for the automated CNC-based fabrication of their timber components. Thus, a lack of coordination between design and construction is evident. This finding resonates with the work of Bailey, Leonardi, and Chong (2011), who stated that in technology interdependent contexts, wherein the output of one technology is used as the input to a second one, actors do not always prioritize coordination. The limited coordination leads to costly redesign and production downtime in manufacturing processes. The currently messy design practice limits the manufacturers’ capabilities to acquire machine-readable 3D-data, which is needed for the production of sophisticated architectural elements.

The focus group discussion with industry experts on how the coordination of digital work between design and production could be strengthened helped to generate some ideas for improved practice. The utility of CNC machines could be increased by streamlining the information flow of BIM design data from the early design stages to production. BIM data would need to be “channeled” toward the persons creating workshop design and CNC data. Moreover, the knowledge of many individuals would need to be bundled and provided to these persons, they would need a complete, highly detailed, and semantically rich model combining all of the disciplines' contributions. This can only be achieved by (1) involving all parties, including the timber-frame manufacturers, early in the process, (2) finalizing the design before production commences, (3) allowing designers more time and resources to create their designs, (4) "frontloading" clients' decision-making to early design stages, and (5) "freezing" the design before construction and production commence. All these measures would enable the creation of BIM models with a greater attention to detail, at a higher quality, and with less in-construction changes than is currently possible.

5.1.5 Overview of the key implications for wood-based construction.

Table 5-1 *Key Implications for Wood-based Construction*

Antecedents	Implications for BIM Deployment
(1) Creating collaborative design spaces	
Collaboration policy and BIM contracts	• Organizing vision of working together in BIM • Common, mutually agreed objective for BIM design • Common understanding of scope, content, and outcomes of digital work • Common understanding of task and technology dependencies • Clear boundaries between partners and disciplinary contributions • Clear responsibilities and roles for team members
New inter-organizational BIM processes	• Work practices can be separated from the logic of 2D design • Procedural guidance for inter-organizational BIM work • Explicates data flow, deliverables, exchange, and file formats • Integration of BIM and CNC data possible
Inter-organizational IT infrastructure	• Integrates a project teams' information systems • Team members edit and retrieve models from a shared platform • Servers, databases, and portals support integrated collaborative work • Facilitates collocated or distributed virtual team work • Software developers needed to "tie" in all design team members
BIM champions	• Champions or BIM managers lead collaborative BIM work • Collaboration network is nurtured and managed inside and across organizations • Practical support for partnership in terms of resources and IT infrastructure
(2) Influence of project characteristics	
Identifying benefits and costs of BIM	• Reliable business cases for BIM collaboration based on building's complexity • Joint assessment of team's collaborative BIM capabilities • Motivates a team in collaboration
Attaining client's commitment	• Client's approval and financial support • Stressing BIM's potential to enhance the process of producing components
Customizing collaboration approach to suit the project	• "One size fits all" approach does not always fit needs of a project • Desired levels of collaboration intensity can be defined
(3) The project team's BIM capabilities	
Raising levels of cooperative BIM capabilities	• Cooperative capabilities are a pre-requirement for integrated design • BIM and CNC competence centers for wood construction • Systematic IS learning in projects (training, super users, guidelines, etc.) • Diffusion of knowledge on conversion of BIM into CNC files
Enabling local systems	• Local systems and hardware need enabling for BIM • Wood contractors' software able to convert BIM data into CNC files • Organizations' hardware equipment fit for BIM-based work • Interoperable BIM systems featuring a common exchange standard
(4) Moving BIM from design to production	
Streamlining the information flow	• Complete, detailed, and semantically rich data for shop drawings and CNC • Utility of machine parks is increased • Early involvement of the entire team • "Frontloading" of client's decision making • "Freezing" of the design before construction commences

The antecedents of collaborative BIM work, as identified in this thesis, are presented in the overview Table 5-1. The antecedents and their potential impact on BIM deployment are presented along four dimensions: (1) creating collaborative design spaces, (2) the influence of project characteristics, (3) the project team's BIM capabilities, and (4) moving BIM from design to production. Some of the presented antecedents may appear generic and are not necessarily "wood-specific." However, all of the antecedents presented below address the shortcomings of collaborative BIM work currently experienced in wood-based construction.

5.2 Theoretical Contributions

This section reflects on the contributions provided by the different theoretical lenses toward understanding the interaction that is taking place between organizations, people, and technology in BIM-based work. The strengths and weaknesses of the theories for understanding BIM-based work are also discussed. In doing so, a contribution is made to the emerging discourse on the inter-organizational work related to the modeling activity when BIM is deployed as a shared design system in project teams (Baxter, 2008; Gal et al., 2008; Linderoth et al., 2011; Wikiforss & Löfgren, 2007). The thesis can be positioned in the body of research conducting multi-actor level studies on BIM's role in collaboration, informed by inter-organizational systems literature. As explicated in Chapter 2 and article 1 (Appendix C), the decision to contribute to this area of research was motivated by a comprehensive literature review. My aim was to study the potential influence of BIM on the inter-organizational work in construction project teams and the requirements for successful deployment of the technology. The design and construction processes identified in three different projects (Cases A, B, and C) have been used as examples to explore how project teams interact based on BIM technology.

The theoretical lenses applied in the research were configuration analysis, cooperative capabilities, and DOI theory. The lenses played a complimentary role in explaining different aspects of BIM deployment. Configuration analysis aided in explaining the inter-organizational alignments, cooperative capabilities provided an understanding of the level of sophistication achieved by a project team working based on BIM, and DOI provided an understanding of the factors that are important in diffusing BIM as a collaborative system. The theoretical lenses are based on a common assumption of IT use as a socio-technical phenomenon, and they all proved to be suited for the study of BIM when taking an inter-organizational perspective. Deploying multiple theories provided analytical leverage and helped to get an in-depth understanding of the antecedents of collaborative

BIM work. In addition, a new conceptual framework termed as *freedom of enactment* has been suggested (paper 4) to account for patterns observed in the empirical data.

5.2.1 Configuration analysis. To my knowledge, the study reported in paper 2 (Appendix C) constitutes the first application of the configuration analysis perspective to study digital work in a construction project. I have positioned my work in the body of research conducting multi-actor level studies on BIM's role in collaboration, where a need for further research ingrained in the literature on IOIS was identified. What made configuration analysis a strong candidate for contributing to this discussion was its capability to focus on issues that are related to collaborative arrangements among organizations.

BIM adoption can be seen as a special instance of IS adoption where both intra- and extra-organizational factors need to be accounted for (Lyytinen & Damsgaard, 2010). Organizations are not the unit of analysis in configuration analysis, but rather a "family" of organizations working jointly based on similar technology (Lyytinen & Damsgaard, 2010, 2011). Moreover, configuration analysis draws from a range of concepts for actor relationships underlying the development of collaborative partnerships. Lyytinen and Daamsgaard (2011) have built their conceptualization drawing from the research on concepts such as trust and suspicion (Hart & Saunders, 1997), power and resource dependencies (Emerson, 1962), and transaction-cost theory (Williamson, 1979). The expected benefits of conducting a configuration analysis include a "more accurate account of […] a multitude of adoption contexts and their dynamics" (Lyytinen & Damsgaard, 2011, p. 504). The theory provided the means for exploring the degree to which BIM was diffused in a project, the collaborative arrangements for BIM work, the agreed key functionality of the systems, and users' attitudes toward joint use of the technology. The configuration analysis perspective can be seen to complement prior work based on more generic theories such as ANT (Latour, 1987) and boundary objects (Star & Griesemer, 1989) by examining "families of interdependent organizations with distinct technological capabilities, and their strategic and structural arrangements as wholes" (Lyytinen & Damsgaard, 2011, p. 497). Its IOIS focus made it a sharp lens for identifying areas in BIM needing managerial attention, as presented in depth in article 2 and Section 5.1. Configuration analysis provided a useful portrayal of industry practice and captured the emergence or failure of organizations to configure their collaborative work.

It has been argued that the study of BIM deployment in construction would require taking the nature of this industrial setting seriously (Linderoth et al., 2011). As configuration analysis is a conceptual model intended to be applicable in multiple, different industrial contexts, it would be of value to make configuration analysis more specific and customized for use in the industrial context of construction projects. This study constituted the first application of the theory in construction, which leaves various opportunities open for suggesting further development of the theory. Based on the findings of this research, three areas in which configuration analysis could be adapted to the context of construction projects were identified: (1) the influence of project characteristics on collaborative work; (2) the influence of decentralized governance structures and decision making on collaborative work; and (3) the reasons behind the lack of initiative displayed by a project design team in aligning their collaborative processes. In the following, these three areas will be elaborated on.

(1) According to the findings from this research, the type of project situation in which the organizations operate influences their collaborative work. It emerged from the empirical data that the importance attributed to collaborative design and the deployment of advanced BIM systems is likely to depend upon the type of project under construction. Buildings can vary in complexity from small-scale residential projects to ambitiously designed one-of-a-kind structures. The type of construction project has been found to influence the way in which organizations appropriate BIM technology. Thus, the key parameter, "mode of appropriation" (introduced in Chapter 2), could be redefined in the following way: "The scope and intensity of potential effects of adopting [BIM] for the participating organization [taking into account the type of project situation]" (Lyytinen & Damsgaard, 2011, p. 499). This would then lead to a more in-depth insight into how project complexity connects to the forming of collaborative partnerships in BIM.

(2) The type of governance structure influences the degree and intensity of cooperation in IOIS (Bensaou, 1997). Construction projects are typically run based on decentralized governance structures and decision making (Dubois & Gadde, 2002). The literature reports that unless economically powerful actors, typically large construction clients or contractors, take the initiative and demand collaborative BIM work, it is unlikely to emerge (Gu & London, 2010). Configuration analysis provides a means to identify power relationships between the powerful and the "obedient" actors in a collaboration (e.g. hub and spoke constellations). These relationships emerge from observing patterns in collaborative work taking place between team members. However, in cases where there is low collaborative activity (e.g. Case A), it becomes difficult to identify such power relationships. Configuration analysis of BIM-based work could be supplemented by

conducting a separate and thorough analysis of the power relationships in a project, even when collaborative activity is absent.

(3) A lack of commitment and investment in inter-organizational ICT has been identified as typical for the construction industry (Linderoth et al., 2011). Configuration analysis has confirmed a lack of initiative by the project team in establishing a collaborative BIM design environment, but does not provide an explicit explanation for why this occurred. While configuration analysis worked well to point out weaknesses in inter-organizational work, it did not explain why nobody felt responsible for fixing them. As stated above, issues related to trust and suspicion may lead to a lack of commitment in collaborative work (Hart & Saunders, 1997). Thus, making the trust among the group of organizations involved more explicit could supplement a configuration analysis. One could, for instance, study the perceived trustworthiness of the project team participants, defined by Mayer, Davis, and Schoorman (1995) as consisting of ability, benevolence, and integrity: “ability is that group of skills, competencies, and characteristics that enable a party to have influence within some specific domain; benevolence is the extent to which a trustee is believed to want to do good to the trustor, aside from an egocentric profit motive; and integrity involves the trustor's perception that the trustee adheres to a set of principles that the trustor finds acceptable” (ibid., p. 497). According to a recent survey among construction professionals in Japan, the three top reasons for their hesitation in working based on BIM were cost consciousness, a lack of time to master and train on BIM software, and the difficulty associated with finding a competent BIM operator or subcontractor (Hiyama & Kato, 2011). The findings reported in this thesis corroborate this work, as the costs associated with collaborative BIM work surfaced as an important factor in preventing the firms from deploying BIM. Configuration analysis could be supplemented by further exploring how the resources required for collaboration (time, cost, equipment, personnel, etc.) influence a project team’s decision to align their inter-organizational structures for BIM.

5.2.2 Cooperative capability. Cooperative capability analysis was chosen for explaining the overall cooperative performance displayed by a project team (Chapter 2). The cooperative performance of two design teams executing projects of different complexity based on BIM technology was assessed and compared (paper 3). The framework applied in this study was the Building Information Modeling Maturity Index (Succar et al., 2012). This framework proved to be a good fit for several reasons: (1) it allowed for capturing team members’ capability and commitment in operating based on BIM; (2) its staged capability model consisting of milestones, and describing the degree and intensity of BIM-based collaborative activity, provided a good portrayal of industrial practice; and (3) applying the maturity-level scale helped in understanding the “quality, repeatability and degree of excellence” achieved when collaborating during different BIM capability stages (Succar et al., 2012, p. 124). This analysis was important for the purpose of this thesis, since it supplements the configuration analysis by exploring the influence of project characteristics on collaborative work. Moreover, conducting this study contributed to the literature on BIM performance (McCuen, 2008; Porwal & Hewage, 2013; Succar et al., 2012) by making explicit that a project team’s commitment in collaborative BIM deployment relates to the complexity of the project under construction.

As has been illustrated in article 3, the perception of BIM’s business value increases with the perceived complexity of a project. Complexity is defined in terms of the number of varied elements of which the structure consists. In the simple project, several actors having high BIM capability decided against using BIM collaboratively. Despite the different levels of cooperative performance displayed by the project teams, none of them achieved an Integrated Project Delivery (IPD) level of sophistication (Matthews & Howell, 2005). The findings imply that a BIM capability assessment at the project outset does not necessarily predict the actual sophistication with which collaborative work will be performed by a project team. Moreover, even when collaborative BIM work is prioritized, project teams face challenges in deploying BIM collaboratively. To complement the explanatory power of BIM assessment tools, it is suggested that a systematic approximation of BIM’s business value considering the complexity of a project should be undertaken. This would be an initial step in managing expectations of what can be gained by BIM-based collaboration.

5.2.3 Freedom of enactment. The fourth article presents a conceptualization developed for linking patterns observed in the empirical data to the root characteristics of project work in construction. Construction projects are very complex in their nature, rooted in their uncertainty and interdependence (Gidado, 1996). The high degree of uncertainty stems from incomplete activity specification, unfamiliarity with the local resources and environment, and the diversity of the materials and people involved. Meanwhile, the high degree of interdependence results from the number of interdependent technologies and the high division of labor that is typical for the construction industry with design professionals covering different areas of expertise (Gidado, 1996). In addition, scholars argue that the construction industry can be seen as a loosely coupled system (Dubois & Gadde, 2002), and that it is characterized as highly fragmented in nature (Howard et al., 1989). Research also reports that construction supply chains are sequential in their nature, having to do both with the procurement strategies and the traditional division of labor that is typical for construction projects (Love & Li, 2000). How industry characteristics influence collaborative work has been identified as an area in need of further research (Linderoth, 2011). Moreover, how the organizing of construction projects influences collaborative work and the lack of initiative of some designers were identified as areas in need of further inquiry in the configuration analysis (paper 2).

Common for both cases was that while architects and consultancies were satisfied with their opportunities to deploy BIM, the manufacturers of the wooden components stated that they lacked the possibility of deploying their BIM systems to the fullest. For example, the architect in Case A stated that he used technology in the way he "liked to do it." Architects avoided using the BIM systems or only engaged with them in a cursory manner (Case A). In Case B, the architect attempted to use the BIM system to a great extent. In general, the manufacturers made improvisations or "workarounds" in the technology use (Boudreau & Robey, 2005; Orlikowski, 2000). This led to costly production, due to additional working hours spent in redesign and errors detected during the process.

At the core of the conceptual model advanced in paper 4 is a construct called the actor's freedom of enactment. The term *freedom of enactment* has been coined to describe the degree of flexibility an actor possesses in performing actions in the BIM system. Moreover, actors' decisions about which technology to enact in practice were led by their perceptions of which way of working would be appropriate in a given situation. How interdependent project actors are on each other's design technology and work, how strongly the organizations are coupled (e.g. business processes and practices), and at what point in time an organization joins the design and construction process are all conceptualized to influence an actor's freedom to deploy BIM technology to the fullest. Freedom of enactment is an important precondition for project team members seeking to partake in collaborative BIM. The freedom of enactment model represents a contribution to the literature on BIM in building construction by offering a conceptualization of how the characteristics of project work influence digital collaborative work in construction.

5.2.4 Diffusion of building information modeling. DOI theory is widely applied by IS researchers to study the adoption of IOIS (Robey et al., 2008). DOI has also been applied by CI scholars to study the diffusion of ICT in the construction industry. Current DOI work in construction is characterized by large-scale survey studies seeking to identify generic factors driving the diffusion of ICT in construction projects (e.g. Peansupap & Walker, 2005, 2006a, 2006b). This work does not differentiate between IOIS and intra-organizational systems. Moreover, studies focusing on the identification of diffusion factors that are useful throughout the entire industry provide only a generic idea of how BIM can be diffused. Peansupap & Walkers' (2005) work provided a useful starting point for our study, however there was overlap between some of the suggested diffusion factors such as "negative emotions toward ICT use (individual factor)" and "frustrations with ICT use (technical factor)". In addition, many diffusion factors were generic in their nature such as "supervisor and organizational support". Such factors would need further scrutiny, as there is no mention of how this support can be mobilized at project level. Moreover, such studies have been criticized and it has been argued that generic diffusion factors fail to provide an accurate portrayal of the "local, complex, networked, and learning intensive features of technology, [and] the critical role of market making and institutional structures in shaping the diffusion arena" (Lyytinen & Damsgaard, 2001, p. 14).

Industry-level, generic ICT diffusion factors were studied in their empirical context. The idea was to "unearth" the concrete, practical steps and management decisions that lead to BIM's diffusion as a collaborative system. For this, a case project was selected in which the design team evidently succeeded in collaboratively creating a highly sophisticated digital prototype of a building by using BIM technology. Based on this, a set of diffusion factors that led to successful BIM-based practice were identified. Analyzing a set of diffusion factors identified in former research in the context of the advanced hospital construction project made it possible to increase the understanding of project-level actions and decisions leading to the successful diffusion of BIM as a collaborative system. For instance, it provided a detailed idea of how construction teams could train and learn when working based on BIM. Moreover, it was possible to develop an understanding of the processes required to diffuse BIM. In addition, the case aided in understanding how the technical infrastructures affording the operation of a functional BIM system could be established. Moreover, the importance of the diffusion context for DOI efforts has been made explicit.

5.2.5 Overview of the key theoretical contributions. An overview of the theoretical contributions of the thesis is provided in Table 5-2. The contributions are presented in the order in which they have been discussed in this chapter. The table summarizes the key contributions from applying these perspectives in my study and how my research can be seen to contribute to the further development of the theories the text presents below. My work has contributed to theory by extending the application of configuration analysis to the construction project management literature, identifying several areas where configuration analysis could be supplemented to better capture the nature of collaborative work in construction projects could be identified. A stronger focus on the impact of the project's nature (e.g. complexity), the required resources (e.g. time, cost, personnel), and the project's organizing of the collaborative work would supplement configuration analysis. My use of the cooperative capability lens to study projects of differing complexity extended the research on BIM performance assessment by making the link between collaborative performance and project complexity explicit. The new freedom of enactment framework offers a conceptualization of the freedom a project team member possesses in deploying BIM systems to the fullest, thereby taking into account an actor's position in the process chain, the degree of coupling among the team members, and the degree of task and technology interdependence. This framework contributes to the BIM deployment research by explicating how better policies for collaborative work could be built. More explicit, it contributed an understanding that increasing the degree of coupling, intensifying concurrent work, and by proactive management of task and technology interdependencies more project members could be enabled to partake in collaborative BIM work. I further extended the application of DOI theory by applying it to study the "local, complex, learning intensive features of [BIM]" (Lyytinen & Damagaard, 2001, p. 14) in a successful case of BIM diffusion.

Table 5-2 *Contributions from the theoretical perspectives*

Theory	**Contributions**
(1) Configuration analysis	Increased the understanding of strategic and structural arrangements for BIM Implications for construction management: (a) Focus on creating a mutually agreed organizing vision for BIM
(2) Cooperative capability	Explicated that a project team's collaborative performance is influenced by project complexity Implications for construction management: (a) BIM's perceived business value changes with a building's complexity (b) Collaboration intensity levels need to be customized for the nature of the project
(3) Freedom of BIM enactment	Offers a conceptualization of how characteristics of project-based work influence digital collaborative work in construction Implications for construction management: (a) Increase the coupling among the firms partaking in construction projects (b) Reduce sequentiality in the project supply chain and involve team members early (c) Manage task and technology interdependence proactively (d) Create awareness among actors positioned early in the supply chain that their use of technology might impact those joining the project later
(4) Diffusion of BIM	Provided an understanding of the project-level actions leading to a successful diffusion of BIM Implications for construction management: (a) Diffusion approach needs to be "tailored" to its context

6 Conclusion

This chapter presents the answers to the research questions introduced in Chapter 1. Additionally, the main limitations and implications for further research are presented. The key implications for theory and industrial practice have been presented in depth in Chapter 5 and an overview can be found in Tables 5-1 and 5-2.

6.1 Answering the Research Questions

The overall research question (RQ) addressed in this thesis is *How can building information modeling support integrated practice in the wood-based building industry?* The RQ has been divided into three sub-questions:

(SQ1) What is the current state of BIM adoption for integration in the wood-based building industry?

(SQ2) What are the predominant social, environmental, and technical barriers for BIM adoption in this industry?

(SQ3) What changes will be required with respect to work processes and interaction between the actors in the industry to achieve improved design and information sharing through the use of BIM?

As explicated in Chapter 1, the individual articles contributed to understanding one or more of the questions asked. Only by combining the findings from the three case studies (A, B, and C, introduced in Chapter 3), did answering the research questions become feasible. In the following paragraphs, the answers to SQ1–SQ3 are first presented and then the main research question is addressed.

SQ1: What is the current state of building information modeling adoption for integration in the wood-based building industry? BIM deployment in projects in the wood-based building industry has been assessed based on a focus group discussion with experts and two examples of BIM use in practice (articles 2, 3, 4, and 5). This research has shown that the wood-based building industry is in the midst of a transition from 2D-based design practices toward BIM-based design. While implementation spreads and some firms begin to deploy BIM systems, not all project team members have developed BIM capabilities. Building the ICT infrastructures required for operating BIM as an inter-organizational system, such as servers, databases, and portals, is currently not focused. Firms that have adopted BIM, concentrate their usage on speeding up the production of disciplinary 2D drawing sets. BIM's functionality for collaborative work is currently left unused in practice. BIM's utilization in wood-based construction is limited to enhancing internal processes, and integrated design linking model representations across several disciplines is not focused in practice. However, some BIM-capable designers coordinate their work by conducting interference checkups based on IFC files. Manufacturers having invested in robotic CNC-based machinery struggle to acquire the 3D parametric data necessary to put their new machines to a purposeful use. Machine parks are left underutilized and CNC technology is used to produce simple elements not requiring intense modeling efforts. When modeling technology is deployed, current practice is characterized by a high degree of improvisation and workarounds.

SQ2: Which are the predominant social, environmental, and technical barriers for building information modeling adoption in this industry? Case studies A and B in conjunction with the focus group discussion allowed for identifying several shortcomings in current practice preventing BIM from being used as a collaborative system (articles 2, 3, 4, and 5). A timber-frame builder summarized current issues by stating: "there are many [clients, architects, consultants, and manufacturers] that do not think BIM is important and […] continue to work in 2D and almost all firms […] are still learning to do BIM." In the following, the social, environmental, and technical barriers for collaborative BIM-based work in wood construction are discussed.

Social. One reason for construction professionals in the wood-based building industry not to promote BIM-based teamwork is that they are used to working alone. Practitioners are not accustomed to concurrent collaboration and rather prefer finalizing designs individually before sharing them with others. While BIM systems are built for concurrent work, design in wood-construction projects is executed sequentially and is gradually developed over time. This is similar to what has been referred to in the literature as a "misfit" between a preexisting culture and business processes and the underlying logic of the new systems (Markus, 2004). The "short-term" business relationships typically found in construction projects amplify the hesitation to collaborate. Building up mutual trust and understanding that is required for collaborative work appears difficult to accomplish in this setting. This misalignment is signified by all those project team members who, despite having BIM capabilities and systems in place, remain excluded from collaborative work due to joining the project late (e.g. manufacturers, contractors). Without a clearly felt need or urgency for changing toward using BIM, project teams continue to work based on 2D CAD technology, traditional design processes, and deploy BIM only to automate 2D drawing production.

Environmental. The wood-based building industry is a tough environment in which to introduce new inter-organizational systems. As illustrated in my thesis, no organization felt responsible for undertaking the necessary investments in project-level ICT supporting collaborative work. Moreover, collaborative BIM-based design is widely perceived as costly and time consuming when compared to conventional 2D-based practice. As the evidence showed, BIM system use is not always perceived as providing unconditional positive implications for resolving the design of a project. Especially in simple projects, BIM is seen as too costly and is regarded as an obtrusive element for effective project delivery. The perceived business value of BIM appears to increase with the complexity of a project. A possible explanation for the hesitation to engage in BIM-based work is that the firm's profit margins are relatively tight, thus limiting the available resources for investments in collaborative technology and related work. Another explanation is that only a few firms possess cooperative BIM capabilities that are sophisticated enough for digital collaboration. From the case studies, it emerged that unless clients demand BIM and are willing to commit considerable additional resources to the design stages, then BIM-based work will not be prioritized, even for complex projects.

Technical. In the wood-based building industry, packaged BIM software solutions such as Cadwork®Wood and HSB®Cad are commercially available and used. However, working together based on "off-the-shelf" solutions provided by different vendors makes collaboration based on a central, shared 3D model difficult (Whyte, 2011). What complicates collaboration further is that project teams in wood-based building deploy non-object (2D, 3D) and object-based (BIM) design solutions in parallel. Seeking digital collaboration thus requires practitioners to convert 2D-based designs into 3D designs constantly, and vice versa, which is costly and time consuming. In addition, establishing project-level IT infrastructures supporting the collaborative work such as BIM servers, databases, and portals is not focused in wood-based construction projects. Moreover, some design team members are unable to partake in BIM-based work since there is a lack of commercially available BIM solutions for their disciplines (e.g. geotechnical engineers, fire-protection engineers). Technical problems resulted, for instance, from a lack of interoperability between BIM and GIS solutions and/or other advanced engineering systems. Another technical barrier for collaborative BIM work is that solutions currently lack the functionality to provide procedural guidance directing users in their interaction with the systems. Partially due to the aforementioned technical barriers, design collaboration is characterized by a high degree of workarounds and improvisation.

SQ3: What changes will be required with respect to work processes and interaction between the actors in the industry to achieve improved design information sharing through the use of building information modeling? The hospital case study reported in article 5 illustrated that the goal to achieve integrated design can only be reached by adopting a new way of thinking that goes against common or conventional wisdom. Current practice in wood-based building is deeply ingrained in traditional ways of working, signified by 2D-based processes being left intact, and/or including contractors and manufacturers in the late design stages. To overcome these barriers, several changes are perceived as necessary: services should be established where experienced BIM users aid the less experienced collaboration partners in creating digital models; guidelines for inter-organizational BIM-based design should be customized for the needs of the wood-based building industry; the role of a central BIM manager or champion should be established; and knowledge on the application of BIM and CNC in wood-based building projects should be disseminated to clients and practitioners. Improving the coordination in terms of BIM system use among the project team members and increasing the awareness that CNC users will need sophisticated and semantically rich modeling data for their production have been identified as areas in need of managerial attention. How coordination in terms of BIM system use can be improved has been elaborated on in Chapter 5 and Table 5-1. This includes building collaborative design spaces, taking into account the influence of project characteristics, considering a project team's BIM capabilities, and insuring that BIM data is moved from the design to production phases.

To achieve full business process integration, the actors would need to establish a shared organizing vision or collaboration policy for BIM. This organizing vision needs to align inter-organizational processes and the functionality of BIM. Actors would need to be "free" to participate in collaboration, which can only be achieved by involving all parties, including the manufacturers, early on in the design processes. Moreover, the design would need to be complete and "frozen" before production commences, limiting design changes throughout the execution. To enable BIM for a wider range of projects, customized collaboration environments need to be engineered, and stakeholders' BIM capabilities would need to be improved by taking a structured approach to IS training. The findings illustrate weaknesses in existing practice and highlight possible improvements.

RQ: How Can Building Information Modeling Support Integrated Practice in the Wood-based Building Industry?

Many manufacturers in the wood-based building industry have invested heavily in robotic CNC-controlled fabrication machinery and BIM. The main purpose of doing so was to use BIM systems to acquire parametric data created by others and to produce wooden components directly without costly redesign by turning BIM files into machine-readable CNC files. The findings of this thesis illustrate how many project teams struggle to work based on BIM and that it is nearly impossible for manufacturers to acquire parametric design data that are sophisticated enough for digital fabrication. Only in complex projects in the wood-based building industry is BIM regarded as an opportunity worth pursuing, and even in these cases, integrated design is seldom achieved. By not investing in the technology and processes required for integration, current design collaboration is characterized by a high degree of workarounds and improvisations, and is limited to an occasional exchange of full-fledged models and control for geometrical collisions based on IFC files. In this thesis, I present a case study of a major healthcare construction project in which designers claim to have succeeded in integrated design. The designers organized their digital collaboration by establishing 1) change agents; 2) a cloud-computing infrastructure; 3) new roles and responsibilities; 4) BIM contracts specifying the desired levels of BIM deployment; 5) an IS learning environment; and 6) by involving software developers to assist designers in overcoming technical challenges and linking previously unconnected designers (e.g. fire protection). These factors have been identified as influential for the successful diffusion of BIM in this project and may serve as an example for the implementation of BIM in projects in the wood-based building industry to support integrated design.

6.2 Limitations

As with any research project, there are several limitations that need to be considered. Generalizing in interpretive research is accomplished by deriving explanations from an empirical context, which should be of future value for other organizations and contexts (Lee & Baskerville, 2003; Walsham, 1995). Therefore, selecting cases requires careful consideration to maximize the value of the explanations obtained for practice and research. In this research, three construction projects were selected for analysis. Two projects were chosen as examples of digital design practice in the wood-based building industry and one case was chosen as a case of advanced BIM practice. The cases included the construction of residential buildings, a public library, and a regional hospital. Together, the cases were considered sufficient to explain digital, BIM-based collaboration in the wood-based building industry and for suggesting how current practice could be improved.

However, my selection of cases had shortcomings. First, other categories of construction projects apart from those named above were not studied. For instance, it would have been interesting to investigate how collaborative BIM-based work unfolds in projects following ultra-low-energy, or zero-energy building standards currently undergoing adoption in Norway and some other European countries. Such projects appear to be a natural application area for advanced BIM systems, as their design is likely to benefit from the energy and airflow simulations that are possible in BIM. Energy efficiency is a timely topic and recent legislation in Norway requiring higher energy standards (NS3700/01) poses challenges to organizations working in the wood-based building industry. However, apart from a few regional pilot projects testing technical solutions for ultra-low-energy buildings initiated by the AgderWood initiative (www.agderwood.no), no such building projects were underway, thus limiting my opportunities to study BIM-based work in this type of project. Moreover, my work is limited in that the study did not include any commercial or infrastructure construction projects. Thus, my findings can be further validated and extended beyond the three projects that were studied.

Second, I developed my view on how firms can succeed in BIM diffusion based on a single case study (the regional hospital). I argue that the explanations obtained aided in the understanding of how organizations can succeed in their diffusion of BIM systems. However, this project was “unique” in that the sophisticated BIM practice displayed by the project team benefited greatly from governmental funding. Moreover, the team was given the opportunity and time to improve their BIM skills in an ongoing project. Thus, the collaborative BIM-based work only became possible by removing some of the resource constraints that are typically experienced in construction projects. My work could thus be complemented by further studies on successful BIM diffusion in other settings.

Third, all my case projects were located in Norway. This context is special since Norway’s standardization body, *Standard Norge,* has been at the forefront in developing standards for BIM-based work in construction. Norway, like its Nordic neighbors Denmark, Finland, and Sweden, has been among the few countries worldwide to embrace BIM technology deployment actively in its construction industry. This is reflected by the large Norwegian governmental clients (Statsbygg, Forsvarsbygg, etc.) who already demand BIM-based work for most of their projects. Moreover, BIM has a prominent place in the current trade literature and is widely promoted by industry-led organizations such as BuildingSMART Norge, which represents 25% of the Norwegian construction industry. Thus, the findings of case studies conducted in the Norwegian building industry may differ from case studies in other countries not promoting BIM to a similar extent.

Last, getting participation from construction professionals for the focus group discussion proved difficult due to their busy schedules. Nonetheless, three of the invited firms responded and sent a good selection of practitioners to participate in the workshop. I did not experience such problems when arranging and conducting the interviews with the industry experts in the case studies, as signified by the 27 individuals who were willing to share their BIM-related experiences.

6.3 Further Research

Several avenues worth pursuing in further research have been identified in this thesis. First, as stated in Chapter 3, my role as a researcher was that of an outside observer. Taking the role of an involved researcher, engaging in organizational day-to-day practices, and participating actively in building a collaborative design space for BIM in the wood-based building industry, could provide a good arena for putting the identified antecedents for BIM’s diffusion as an inter-organizational system to the test. This work could focus on building a stable modeling data flow linking design and production by linking BIM and CNC. An action research approach with a researcher actively promoting and championing BIM collaboration would also provide a first-hand account of what it would be like to serve as a mediator in inter-organizational BIM work and the challenges emerging around this role.

Second, it has been identified in this thesis that project complexity matters when design teams decide whether to collaborate based on BIM. Moreover, the thesis offers an initial conceptualization of the relationship between design productivity, project complexity, and collaboration. Further research is needed to examine the interrelationship between project complexity and the actual business value of BIM-based collaboration. This work could adopt a comparative case study approach covering a broad array of projects differing in complexity in conjunction with using IS evaluation techniques such as post-implementation reviews or balanced scorecard, or the IS success model (DeLone & McLean, 2003) to compare, in retrospect, what has been gained by using BIM in these different projects. This type of research would further improve the ability of design teams to respond adequately to complexity.

Third, collaborating with actors who do not yet work based on BIM technology is challenging. The thesis has highlighted that structured approaches to IS learning at project level and industry competence centers would be necessary to enable design teams' collaborative work. Further research could inquire as to which IS learning approaches are best suited to improve collaborative BIM capabilities in projects, and how regional competence centers or clusters could be built to trigger more integrated work in the wood-based building industry. In the Agder region of Norway, the existing industrial technology cluster for the oil and gas industry could serve as an inspiration for how such competence centers could be established for the wood-based industry.

Fourth, the freedom of enactment framework developed in this thesis provided a new understanding of the antecedents and impacts of the actors' freedom of enactment, particularly in the use of BIM systems. As an initial validation, data from two construction projects were used to test the plausibility of the framework. However, the list of both the antecedents and impacts of freedom of enactment are not exhaustive and this work could be complemented by further research testing the framework. In addition to validating the framework, further research could seek to identify other possible antecedents for the freedom of enactment. This could be done by studying the applicability of the framework in a wider industrial context involving a range of projects.

Fifth, software facilitating the communication could be useful to aid a more organized use of BIM technology during collaboration. While some efforts such as developing the Design Process Communication Methodology (DPCM) have been undertaken, such solutions are not yet commercially available (Senescu, Haymaker, & Fischer, 2011). These systems could include features directing users in their interaction with the system and collaborative scripts supporting the team process (Briggs et al., 2003). In addition, "work sharing" functionalities supporting synchronous collaboration are currently only available when working based on systems provided by the same vendor (e.g. Autodesk®Revit); these functionalities could be further developed to allow for synchronous data exchange between systems provided by various vendors. This would further improve practice by making it possible to engage in concurrent collaborative work beyond exchanging IFC-based files.

Last, based on mapping of the topic areas in BIM-related research (article 1) and the findings of my research, I argue that BIM technology and its use in the AEC industry is a field in need of further IS research. Examples of intriguing questions for further IS research include what is the value of virtual teams and cloud computing technology for construction projects? How can the content produced in BIM design be managed to be useful for facilities management? And how can BIM technology be further improved to better serve its purpose as an environment for digital collaboration?

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Appendix A: Examples of Interview Questions

a) Semi-structured interview guide: Case study A: Residential project

(The guide is based on the key concepts that are important in configuration analysis. The related concepts are shown in parenthesis.)

1. Personal background

Firm/Education/prior occupation/Job: Currently working on/Work experience (years)/Age/IT-related experience/ IT-training received by employers current and past/IT skills

2. Communication in the "Case A" project (key-functionality)

How do you use **written text** in project communication (e.g. technical writing…)?
Tools? ICT use? Distribution? Purpose? Who gets what? Record keeping?

For which purposes do you use **physical items** such as material samples or physical scale models in communication (information presented within the field with the purpose of easing decision-making)? Record keeping? ICT use?

For which purposes do you usually use **images** in communication (a picture or photo of a scene or an object) in communication? Do you use IT to distribute, manage, and store the images?

For which purposes do you rely on **verbal** communication? Which ICT do use (smartphones, VOIP, audio/video conferencing)? Which technology do you use in meetings? Do you record meetings (protocols, recordings…)?

For which purposes do you use **graphic or visual** representations on computer screens or on paper in communication (examples include construction drawings, diagrams, symbols, geometric designs, maps, and engineering drawings)?

If you think about your daily work, which form of communication (verbal, written text, images, graphic, or visual representation) occupies most of your time (all of the time used in communication including the creation and management of the data)?

3. Design tools in the "Case A" project (key-functionality)

Which digital tools do you use to create construction design (2D Auto CAD, 3D CAD, BIM, GIS)?

Are you satisfied with design collaboration among the partners in the project?

How happy are you with the information exchange between the project partners with regards to the interoperability of programs?

Are you satisfied with the design software you and your partners currently use?

Does everybody in the project use 3D CAD and, if not, is that a problem?

If anything, what would you change to make design and collaboration easier?

4. Common agreements and rules in the "Case A" project (organizing vision)

Are there some "**unwritten or written** data-exchange" **rules** regulating how information is exchanged?

Is there a common understanding of **who delivers** what information in what **format** at what **time** in the project?

Does your firm have certain organizational standards or guidelines for communication with others?

Did your firm do prior business with the partners in this project?

How well do you personally know the people in the other firms?

5. How do you see the role of your firm in the project? (Structure, mode of interaction, and mode of appropriation)

When compared to the other firms in the project, do you think you are well equipped with the ICT tools and technology?

When compared to the other firms in your industry, do you believe that your technical department is strong and innovative and outperforms others?

In your opinion, do you have enough manpower to produce the design on time and at the quality needed?

If you think about your ICT skills, would you like to learn more about some programs, and which would those be?

6. IT and strategy (mode of appropriation)

Do you believe communication and information technology is given high importance by your firm's management?

Do you think your organization has a clear IT strategy in place to keep abreast of the latest technology?

Do you think in the long run that ICT can change the processes in the industry? Or will it be used to make existing processes faster?

7. A look into the future (mode of appropriation)

Where do you see the biggest problems of the current technology (GIS and or BIM)?

Does the technology provide you with capabilities to do your job better, to arrive at goals?

Did the use of BIM/GIS change the way you work?

Do you expect the technology to change the way you work in the future?

If you could change the technology to make it a better tool for your purposes, what would you change?

Did you change or customize the technology to make it more convenient for you to use?

Thank you so much for your time.

Appendix B: Examples of Data Analysis

Example 1: Case C: Diffusion of BIM

Merschbrock: So did this BIM use plan [how to collaborate in BIM] emerge in the project?

Interviewee: In every project, we stand on the shoulders of the previous project, so I already had done that on a couple of projects. But of course you have different actors, you do not have the same possibilities, you have … you come from a set of companies with one understanding to a set of companies with another understanding, other software, and other ways of working, so it's … you cannot do copy and paste, but you can use the ideas.

Node assigned: Managerial diffusion factor

Example 2: Case C: Diffusion of BIM

Merschbrock: Is your project an example of an advanced, leading-edge BIM practice?

Interviewee: We are obviously more early then we believed at the start and we did not expect to get so many problems. For example, when we used Navisworks to link the model and the time schedule, and we worked with the visualizations, we noticed that this obviously had never been done in really large projects before. It worked very well to do simulations, but it did not work at all to update the models according to the schedules all the time. In addition, it does not work when you have new objects in the model. That is also one of the things that we learned throughout the process.

Node assigned: Technical diffusion factor

Example 3: Case A: Configuration analysis

Merschbrock: Are there common arrangements or rules, plans [in this project for collaborative BIM work]? Is there a common agreement among all parties in the project where people sat together and clarified this is how we do the data exchange?

Interviewee: In my experience, I have only very few times had a talk with one of them [other designers] as to how the communication should be. So usually, we do not talk about this. I try to do as well as I can, and very often, it's not the communication, it's the speed of the communication related to what we are working on. When I ask the consulting engineer something urgent, then I expect an answer as soon as possible; however, the response will come "maybe" this week or even at the beginning of next week.

Node assigned: Organizing vision

Appendix C: Research Publications

1. Merschbrock, C., & Munkvold, B. E. (2012). A research review on building information modeling in construction: An area ripe for IS research. *Communications of the Association for Information Systems (CAIS)*, *31*, article 10, 206–229.
2. Merschbrock, C. (2012). Unorchestrated symphony: The case of inter-organizational collaboration in digital construction design. *Journal of Information Technology in Construction (ITcon)*, *17*, article 22, 333–350.
3. Merschbrock, C., & Munkvold, B. E. (in press). How is building information modeling influenced by project complexity? A cross-case analysis of e-collaboration performance in building construction, *International Journal of E-Collaboration (IJeC).*
4. Merschbrock, C., & Wahid, F. (2013). Actors' freedom of enactment in a loosely coupled system: The use of building information modeling in construction projects. *Proceedings of the 21st European Conference on Information Systems (ECIS)*, Paper 124, Utrecht, The Netherlands, 5–8 June.
5. Merschbrock, C., & Munkvold, B. E. (2013). Improving inter-organizational design practices in the wood-based building industry. *Proceedings of the 7th Nordic Conference on Construction Economics and Organisation* (pp. 479–489), Trondheim, Norway, 12–14 June.
6. Merschbrock, C., & Munkvold, B. E. (2014). Succeeding with building information modeling: A case study of BIM diffusion in a healthcare construction project. *Proceedings of the 47th Hawaii International Conference on System Sciences (HICSS)*, (pp.3959-3968), Big Island, Hawaii, 6–9 January.

Article 1

Merschbrock, C., & Munkvold, B. E. (2012). A research review on building information modeling in construction: An area ripe for IS research. *Communications of the Association for Information Systems* (CAIS), 31, article 10, 206–229.

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A Research Review on Building Information Modeling in Construction—An Area Ripe for IS Research

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Communications of the Association for Information Systems

CAIS

A Research Review on Building Information Modeling in Construction—An Area Ripe for IS Research

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Abstract:

This article presents a review of the research on Building Information Modeling (BIM) in construction, with the aim of identifying areas in this domain where IS research can contribute. The concept of BIM comprises an infrastructure of IT tools supporting collaborative and integrated design, assembly, and operation of buildings. This integrated construction approach, with all stakeholders editing or retrieving information from commonly shared models, requires major changes to well-established processes, organizational roles, contractual practices, and collaborative arrangements in the construction industry. Through a review of 264 research articles on BIM, we found that this research spans a wide area of technological and organizational topics, of which many have a clear resonance to focal areas in IS research. Our analysis shows that IS, to some extent, serves as a reference discipline and that theories used in IS research are also informing contemporary BIM research. The following areas in need of further IS research were identified: studies on the relationship between BIM's functional affordance and human agency, adoption and use of BIM for inter-organizational collaboration, the influence of organizational culture on BIM practices, the capabilities of BIM for transforming industry practice, and identifying the business value of BIM. Considering that a well-established knowledge base in IS research can be drawn upon for studying these issues, combined with the exciting potential of BIM for transforming a major industry such as building construction, we conclude that BIM is an area ripe for IS research.

Keywords: Building Information Modeling; architecture, engineering and construction; inter-organizational systems; IT and collaboration; IT innovation; literature review

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Communications of the Association for Information Systems

A Research Review on Building Information Modeling in Construction—An Area Ripe for IS Research

I. INTRODUCTION

In recent years, many companies in the Architecture, Engineering, and Construction (AEC) industry have realized major IT-based change processes in their operations [Gal and Jensen, 2008]. The traditional paper-based and two-dimensional Computer Aided Design (CAD) tools are gradually being replaced by three-dimensional technologies. These technologies, commonly referred to as Building Information Modeling (BIM), are emerging IT-based information systems which promote collaborative and integrated design, assembly, and operation of buildings. BIM can be best described as a platform of IT tools employed to design virtual models seeking to present all physical and functional characteristics of a building [NIBS, 2007]. Moreover, these models are used as a basis for enhancing inter-organizational collaboration [Shen, Hao, Mak, Neelamkavil, Xie, Dickinson,Thomas, Pardasani and Xue, 2010]. Some researchers state that use of BIM technology offers a more democratic, participatory approach to construction design by allowing for improved cross-discipline participation from architects, planners, and contractors [Azhar, Hein, and Sketo, 2008; Isikdag and Underwood, 2010b]. Moreover, it is claimed that these technologies allow focusing on collaboration and the sharing of ideas, as opposed to creating rigid and singular design outcomes. However, an integrated construction approach, with all stakeholders editing or retrieving information from commonly shared models, requires many changes to well-established processes, working routines, information infrastructures, organizational roles, contractual practices, and collaboration practices [Gal, Lyytinen, and Yoo, 2008]. Additionally, corporations are forced to change their traditional mindsets and to "… overcome the tension between their distinct backgrounds…" [Gal et al., 2008, p. 290].

As we document in this article, many of the current research challenges related to adoption and use of BIM in the building construction industry have a clear resonance with focal areas in information systems (IS) research. Still, this area of research has been largely neglected in mainstream IS research. Most of the research on BIM has so far been published in engineering disciplines such as construction informatics (CI), which seeks to bridge the gap between computer science and construction [Björk, 1999; Turk, 2006]. In a recent review article in *CAIS*, Nevo, Nevo, and Ein-Dor [2009] argue for the need for revisiting the area of CAD/CAM technologies in light of the recent development in the impact of these technologies on industrial practice. Our article intends to follow up on this call by presenting an overview of the nature and scope of research on BIM based on a review of 264 journal articles and using this as the basis for discussing how IS research can further contribute to this research domain. The intended contribution of this article is to draw the attention of the IS community to the potential of BIM as a relevant and interesting topic area for IS research, as well as increasing the role of IS as an important reference discipline in this domain [Baskerville and Myers, 2002]. Further, IS research studying the organizational impacts of BIM technology in AEC organizations could also develop knowledge useful beyond this sector of the industry, and similar technologies used in product design might be better understood as well [Nevo et al., 2009]. For example, researchers interested in the impact of Virtual Worlds on product design might draw from research on the organizational impact of CAD/CAM technologies [Nevo et al., 2009].

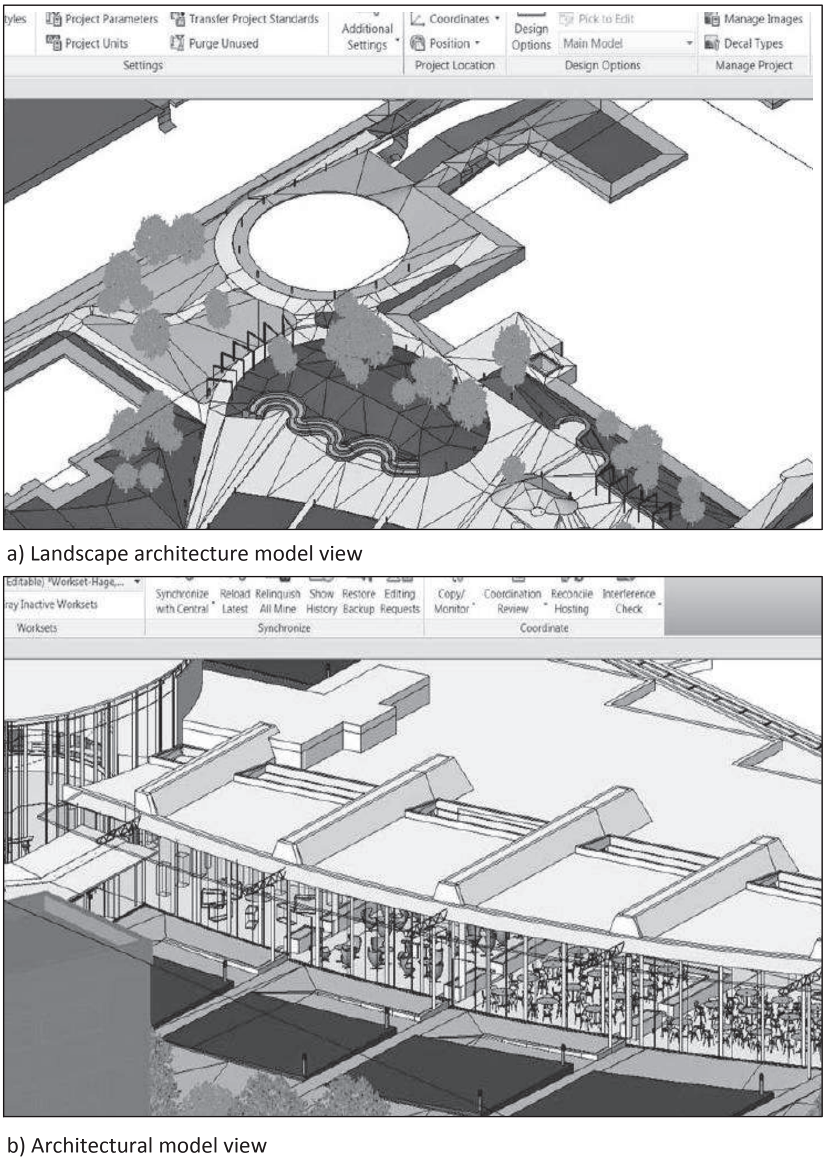
The next section introduces the BIM concept and the construction informatics research field, including the framework guiding the research review. Section III presents the methodology applied for the literature review. The findings from the review are presented in Section IV, and the implications for IS research are discussed in Section V. The concluding section summarizes the contribution of the article.

II. INTRODUCING THE RESEARCH DOMAIN

Building Information Modeling: From 2D to 3D Based Construction

Buildings are typically one-off products made specifically to a customer's order, and the construction is executed as project-based work. Traditionally, construction design services are delivered by multiple organizations where each party prepares a set of paper drawings covering their area of expertise. Design services to construction projects are provided by architects, structural engineers, electrical engineers, plumbing and ventilation engineers, landscape architects, construction firms, and specialized subcontractors, among others. This practice implies that, for simple construction projects, hundreds of paper drawings are produced. These paper drawings are traditionally managed and distributed by the respective contractor's site management.

Virtual modeling technologies became applicable for the AEC industry in the late 1990s. At that time, the term *Building Information Modeling* (BIM) was coined to describe these technologies [Isikdag and Underwood, 2010a]. Moreover, *Virtual Design and Construction* (VDC) is a term frequently used to describe product and process modeling in the AEC industry [Fischer and Kunz, 2004]. Virtual design requires changes in the AEC industry's daily practices. The practical creation of common virtual building models requires a joint effort and close collaboration by all parties providing design to the construction project. In contrast to traditional construction design, in virtual design each party prepares their contribution to a common building model in the form of a specialist model covering their area of expertise. The architect creates a model signifying the shape and outer appearance of the building; the structural engineer creates the structural design model; the heating, ventilation, and air conditioning designer (HVAC) contributes a model on building systems; and so forth. These specialist models need to be joined into a central model of the building aligning all its components. This design practice and its underlying logic of co-creation requires effective handling and timely sharing of information amongst all the diverse parties involved in the project. To illustrate the different foci of subject matter experts in modeling, Figure 1 contrasts a landscape architect's specialist view (upper) versus an architectural view (bottom) of the same building. The landscape architect's model is solely concerned with the outdoor facilities, whereas the architectural model is concerned with the building's shape.



b) Architectural model view

Figure 1. Office Building in Sandsli, Bergen, Norway—Specialist Model Views (courtesy of Sissel Øye, Sweco Norway AS)

Many researchers claim that virtual modeling technology yields several benefits for communication and information sharing in the construction industry, including increasing design transparency, rapid design visualization, rapid and accurate information about changes increasing clarity, and amount of detail which can be communicated in construction design, better decision support, and improvements in engineering design quality in terms of error-free design [Linderoth, 2010; Manning and Messner, 2008]. Additionally, these tools are believed to allow for effective collaboration and information sharing across the organizations involved in a construction project. However, some researchers are less enthusiastic and voice concerns regarding the threshold for successful uptake of this technology. Skeptics argue that the complexity of BIM implementations can be compared to moving from old accounting packages to ERP [Bew and Underwood, 2009]. It is argued that BIM requires the formal management of processes within and across organizations on a consistent repeatable basis, which contradicts traditional working practice in the AEC industry [Bew and Underwood, 2009]. Others see the costs involved to be a major barrier to the transition from 2D CAD to BIM. Last, product vendors add to the complexity by releasing a multitude of applications while common data exchange standards still evolve. Hence, it can be argued that the introduction of virtual modeling technology yields promising opportunities and, at the same time, many challenges for the AEC industry that affect all aspects of the construction lifecycle ranging from design to the operation of buildings.

Previous IS Research in Construction CAD/CAM

Computer-Aided Design & Manufacturing Systems (CAD/CAM) have earlier been a prominent group of IT artifacts studied in IS research, especially throughout the period from 1977–1981 when these topics accounted for 12 percent of all work published in the *MIS Quarterly* [Nevo et al., 2009]. Much IS research in the eighties was motivated by rationalization and automation ideas, and early work published on CAD/CAM debates CAD's role as an information system to speed up the design processes. Thus, multiple studies address CAD's potential to reduce design lead times and increase design quality and productivity through automation of manual sketching processes (e.g., Doll and Vonderembse, 1987). The focus in early research work lay on studying the productivity of designers at individual, group, organizational, and industrial level [Baxter, 2008]. In the 1990s, researchers' focus shifted towards studying networks of organizations interacting by the means of two-dimensional CAD/CAM [Henderson, 1991]. However, the interest of IS research in CAD/CAM topics declined throughout the nineties, and CAD/CAM "has briefly grabbed the attention of IS researchers but has since all but disappeared…" [Nevo et al., 2009, p. 236]. Nevo et al. [2009] do not provide any explanation for this decline in attention and suggest that this be addressed in further research. Thus, we can only speculate on the potential reasons for this. First, the "rapid and continuous rate of change associated with information technologies" [Benbasat and Zmud, 1999, p. 5] leads IS researchers and editors to lookout for emerging technologies that represent novel areas of application to maintain practical relevance. Thus, the "hype" of CAD/CAM in the early period around 1980 could be expected to drop after use of this technology became the industry standard. Second, with this topic being closer to the core of engineering design disciplines, it could be expected that the further development on CAD/CAM would rather be published in engineering journals (see Section III for examples of such outlets). Third, as the review by Nevo et al. was based only on the two top journals in IS (*MIS Quarterly* and *Information Systems Research*), it is possible that research on CAD/CAM topics have been published in other outlets in the increasing list of IS journals and conferences. In support of this, a search on the topics of "CAD" and "CAM" in the AIS eLibrary resulted in a total of more than 800 hits for the period of 1982–2012, indicating that the topic did not ever disappear from the scene.

The technological advancements from two-dimensional to three-dimensional CAD/CAM technologies have also triggered renewed research interest in this topic area in IS research. As our review is especially concerned with the modeling applications deployed in the AEC industry, we discuss contemporary IS literature concerned with three-dimensional BIM modeling technologies in construction. Digital design and communication and coordination practices in the AEC field are, for instance, subject to current discussion within the IS sub-disciplines of Computer Supported Cooperative Work (CSCW) and Participatory Design (PD). CSCW scholars discuss the role of CAD plans, scale models, virtual models, and further artifacts in communication. Their work is largely focused on direct observations of how ICT artifacts shape organizational work practices and is theoretically ingrained in the "representational artifacts and boundary object theory" [Star and Griesemer, 1989; Star, 1989] and the concept of "ordering systems" [Schmidt and Wagner, 2004]. Wagner, Stuedahl, and Bratteteig [2010], for instance, stress the importance of physical or digital artifacts for communication "… in making the invisible visible, specifying, making public, persuading others (of a design idea)" [Wager, et al., p. 59]. Current CSCW research is concerned with the study of human behavior, work practices and sketching tools in BIM mediated design [Christensen, 2007; Safin, Delfosse, and Leclercq, 2010; Tory, Staub-French, Po and Wu, 2008].

However, within mainstream IS few scholars have contributed to the discussion on topics related to three-dimensional BIM modeling. The IS work identified addresses topics such as whether the use of modeling technologies leads to innovations or improved inter-organizational collaboration in the AEC industry [Berente, Baxter, and Lyytinen, 2010; Boland, Lyytinen, and Yoo, 2007; Gal et al., 2008]. Moreover, some research discusses BIM's potential to transform and revolutionize organizational processes in the AEC industry beyond process automation [Ahmad and Sein, 2008, 2010]. These studies are good examples for IS scholars seeking to bridge the gap between IS and construction informatics research, but there is need for further IS research in this area. Contemporary IS research on BIM draws from a limited empirical base and relies largely on case studies of exceptional leading-edge AEC firms known for their innovativeness and IT capabilities (e.g., U.S.-based Ghery

Partners). The focus of this research is largely to point at avenues for further research work within the topic area of representational technologies and their organizational impact.

The Field of Construction Informatics

According to Turk [2000], construction informatics is a distinct research discipline with chairs and departments established in universities around the world. Historically, several wordings have been used to name the discipline, for example, "computer integrated construction," "computing in civil engineering," "information technology in construction," and "information and communication technology in construction" [Turk, 2007]. Some of the most influential CI journals are *Automation in Construction, Journal of Computing in Civil Engineering, Advanced Engineering Informatics, Journal of Information Technology in Construction, Computer-aided Civil and Infrastructure Engineering,* and the *Journal of Construction Innovation*. The domain of interest to the CI field comprises IT-oriented topics spanning several AEC disciplines, such as integration, product modeling, construction documentation, engineering design cycles, and concurrent engineering. Additionally, the IT generated implications for the lifecycle phases of construction projects are of interest to the field. CI is thus an interdisciplinary field related to both IT and construction. IT/IS-related topics have been on the agenda for the AEC industry since the 1960s [Turk, 2006] when AEC corporations first started using computers. CI as a field of applied science evolved in response to the IT/IS-related construction specific issues and unique requirements of the AEC industry [Turk, 2006]. Several CI scholars have developed ontology-grounded frameworks to classify the research produced within their field. In what follows, two different frameworks are introduced and discussed to provide an understanding of the nature of this work. The "BIM Research Compass" developed by Isikdag and Underwood [2010a] (Figure 2) is a classification model reflecting current research directions concerning the BIM paradigm. Their article summarizes a book edited by fifty leading CI experts seeking to map the scope of BIM research. Thus, their framework provides valuable insight on the major streams of research produced on the topic area of BIM within the CI community. Isikdag and Underwood [2010a] identify twelve research directions for BIM, as depicted in Figure 2 and defined in the following.

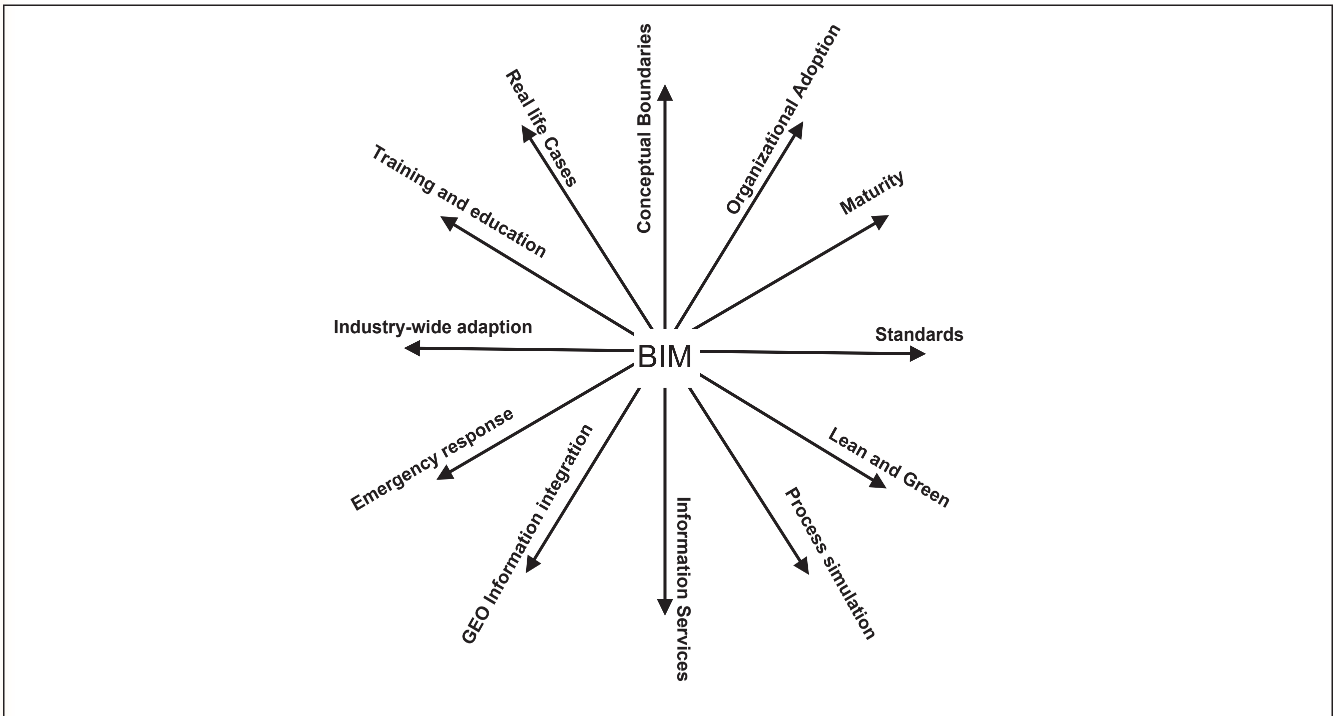


Figure 2. BIM Research Compass (Adapted from Isikdag and Underwood, 2010a)

- *conceptual boundaries;* includes research exploring the scope and limitations of the BIM paradigm
- *organizational adoption;* includes research work on the organizational adoption of BIM together with the AEC industry's approach to contracts and education
- *maturity;* includes research on the organizational readiness in terms of processes, technologies, and methodologies to enable BIM
- *standardization;* covers topics on data level interoperability such as IFC (Industry Foundation Classes)

- *lean and green;* includes research on the effects of BIM on sustainability and productivity within construction operations
- *process simulation and monitoring;* includes research on construction process visualization
- *building information services;* includes research on BIM interoperability over Web servers
- *building geo-information integration;* covers research on the integration between geospatial information systems and BIM
- *emergency response;* includes research work to enable BIM as simulation models for hazards such as fire, earthquakes, gas leakages, and possible terror attacks
- *industry wide adoption;* includes research work measuring and benchmarking BIM uptake on a national industry-wide level
- *education and training;* includes research work related to BIM education
- *real-life cases;* includes BIM case studies within an industry setting

The framework chosen to support the classification within this literature review is Turk's [2007] "Research Themes in Construction Informatics," developed based on a single-step Delphi method approach supported by a survey of fifty researchers within the European CI community. Turk's framework allows for identifying a large variety of topics and research streams, which adds to the quality of the review presented in this article, since it is intended to understand the scope of the CI research. The framework distinguishes between core themes and support themes in CI research. Core themes is defined as topics where original and construction specific knowledge is created, while support themes are topics where knowledge could be transferred from other research disciplines. Table 1 presents a categorization of the core and support themes. The first category of core themes, *common infrastructures,* includes research on shared portals, online applications, mobile computing, Internet applications, and legal considerations of IT. The second core theme category, *communication,* includes all forms of IT-enabled communication, from software-machine robotics to human–human communication topics (e.g., e-mail). Third, the *processing* category includes all research topics related to the creation, management, publishing, and retrieval of data. Turk's definition of support themes include a broad range of themes related to software *deployment* and the socioeconomic *impact* of the technology. Further, support themes are *needs,* as the category for research directed at identifying and suggesting research avenues to pursue, and *transfer* being the category for topics related to the development and teaching of industrial best practices towards using ICT.

Table 1: Research Themes in Construction Informatics [Turk, 2006]

Core and support themes	Category	Themes
core themes	common infrastructures	collaboration, concurrent engineering infrastructures e-business infrastructures electronic legal infrastructures
	communication and coordination	person–person communication technologies software interoperability and integration human–computer interaction machine–computer interaction
	processing	computationally intensive applications knowledge intensive applications modeling and drafting databases, information retrieval knowledge management
support themes	deployment	business process reengineering organizational implementation
	impact	economic environmental socio cultural construction safety
	needs	roadmaps for future research
	transfer	best practice education software development standards

III. METHODOLOGY

A well-structured and solid literature review enables researchers to identify under-researched topics and research gaps. Knowledge about previous work is essential to make informed choices about directions for further research work [Webster and Watson, 2002]. The review in this study can be considered to be a scoping study [Arksey and O'Malley, 2005], seeking to examine the extent, range and nature of the research activity on three-dimensional BIM topics. As pointed out by Arksey and O'Malley [2005], "identifying gaps in the literature through a scoping study will not necessarily identify research gaps where the research itself is of poor quality since quality assessment does not form part of the scoping study remit" (p. 7). BIM-related topics are of an interdisciplinary nature at the crossroads of IS/IT and construction [Turk, 2006]. Thus, the literature review has been designed to cover the breadth of available literature, allowing for the identification of journal articles across several research disciplines. Previous reviews in this area have largely focused on journal articles or conference proceedings originating within the CI field (e.g., Amor Betts, Coetzee and Sexton 2002; Björk, 1999).

Table 2: Literature Search Design

keywords	[a] 3D Modeling AND construction [b] 3D Modelling AND construction [c] BIM AND construction [d] ICT AND construction [e] "Building Information Modeling" [f] "Building Information Modelling" [g] "Virtual Design and Construction" [h] "VDC" AND construction		
database and date assessed	[a] Elsevier SciVerse Scopus assessed 14.03.2011 [b] Elsevier SciVerse Scopus assessed 20.03.2011 [c] Elsevier SciVerse Scopus assessed 14.03.2011 [d] Elsevier SciVerse Scopus assessed 20.03.2011 [e] Elsevier SciVerse Scopus assessed 04.05.2012* [f] Elsevier SciVerse Scopus assessed 04.05.2012* [g] Elsevier SciVerse Scopus assessed 04.05.2012* [h] Elsevier SciVerse Scopus assessed 04.05.2012* (*cutoff date 31.12.2010)	Return	[a] 288 [b] 265 [c] 133 [d] 204 [e] 149 [f] 149 [g] 17 [h] 22
Scopus search details:	[a] (TITLE-ABS-KEY(3d modeling) AND TITLE-ABS-KEY(construction)) AND DOCTYPE(ar)) [b] (TITLE-ABS-KEY(3d modelling) AND TITLE-ABS-KEY(construction)) AND DOCTYPE(ar)) [c] (TITLE-ABS-KEY(bim) AND TITLE-ABS-KEY(construction)) AND DOCTYPE(ar)) [d] (TITLE-ABS-KEY(ict) AND TITLE-ABS-KEY(construction)) AND DOCTYPE(ar)) [e] (TITLE-ABS-KEY("building information modeling") AND DOCTYPE(ar)) [f] (TITLE-ABS-KEY("building information modelling") AND DOCTYPE(ar)) [g] (TITLE-ABS-KEY("virtual design and construction") AND DOCTYPE(ar)) [h] (TITLE-ABS-KEY("VDC" AND construction) AND DOCTYPE (ar))		
# relevant articles	264		
*The literature search was extended on the basis of suggestions from one of the reviewers. Only articles published before 2011 were included in this additional search, to enable comparison with the original sample of articles.			

Documenting the literature search methodology is a crucial part in any review study [vom Brocke, Simons, Niehaves, Riemer, Plattfaut, and Cleven et al., 2009]. In our review we applied a six-step process to identify a relevant and representative sample of articles, based on a framework for literature search presented by vom Brocke et al. [2009]:

1. The SciVers Scopus database was selected as the source for the article search. This is the largest database of peer-reviewed literature in the world, including over 41 million records (in comparison, Science Direct includes 10 million full-text articles). Therefore, the database is considered suitable to scope the nature of the field under study.
2. The review was conducted only on journal articles, considered to be representative of the main research conducted in this area.
3. Keywords, search criteria, and return of articles are presented in Table 2. The search terms "BIM," "3D Modeling," "VDC," and "ICT" have been used to be able to identify the full breadth of BIM literature.
4. All articles including abstracts were exported to an EndNote X4 library.
5. The initial screening for relevance, removal of double occurrences, removal of editorials for special issues, and exclusion of irrelevant articles to the purpose of the study, e.g., biochemistry, medical imaging, and

construction ICT topics other than BIM and 3DM (e.g., EDI or mobile technologies) left a total sample of 264 articles.

6. The articles were categorized according to the classification model presented in the previous section of the article. The search functions in the EndNote X4 library were used to support the classification.

The articles in the sample were classified according to the framework in Table 1. Further, overviews of the number of articles by publication year and publication outlet were produced. The results of this classification are presented in Section IV. The methodology utilized has several limitations. The first limitation is that the review within this article was solely conducted on journal articles, leaving potentially relevant conference proceedings, book chapters, and other literature sources aside. Furthermore, the research is limited to one database which includes only English language publications, therefore, relevant literature in other languages is excluded from this study. Furthermore, the literature review was conducted with the intention to scope a variety of BIM-related research topics within a construction setting. While the journal frequency analysis serves to give an overview of the relative focus on the different topics, this quantitative approach reflects neither on the influence of the respective outlet channels nor on the influence of single articles within this field. An additional limitation is the breadth of the study due to its scoping nature, implying that the literature review strategy chosen prioritizes general understanding of the field under study over in-depth understanding of single research subtopics.

IV. FINDINGS

This section reports the findings of the analysis conducted on the 264 articles under study. Figure 3 illustrates how research interest in this topic area in terms of number of articles published has risen almost exponentially from 1996–2010, implying that BIM is a very timely topic. This observation aligns with the rapid development of BIM technology in recent years. However, a limitation of the proposed timeline analysis is that it is based only on journal publications. Arguably, journal publications are often delayed with regards to the time of study; nevertheless, the results indicate a growing research interest in this field of study.

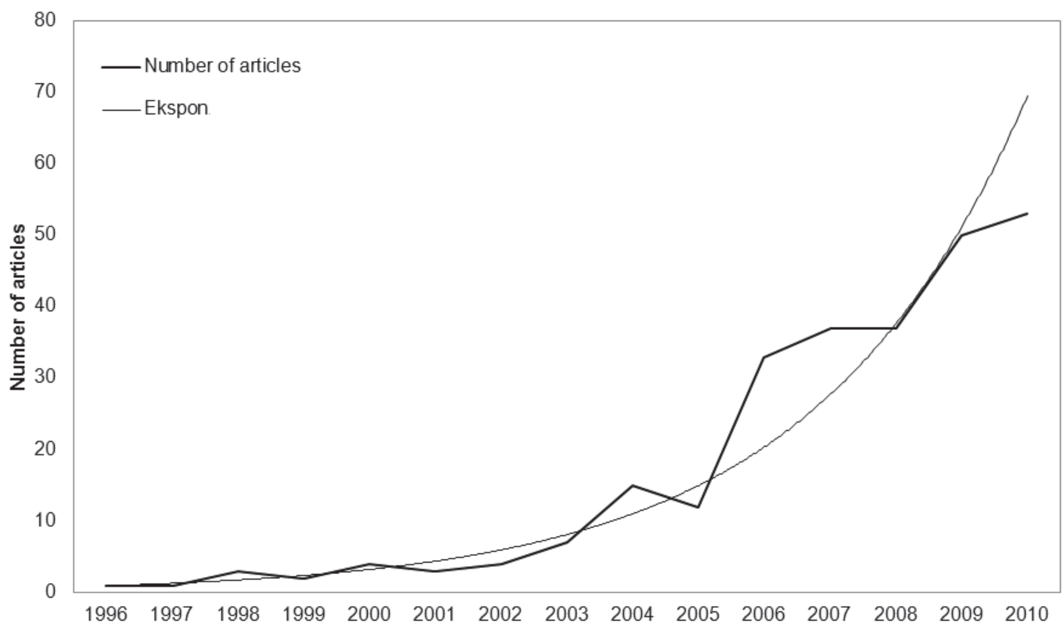


Figure 3. Article Output per Year in the Area of BIM, VDC, and 3D Modeling

The top twenty list of journals contributing to the BIM discussion is presented in Table 3. As expected, CI journals are in the lead and populate the top three positions. Automation in construction has by far the largest publishing volume of the journals studied. This has also been recognized by Björk and Turk [2005] in their study on publishing practice in the CI field. Automation in construction addresses foremost readers interested in design computing topics. However, construction management and the engineering disciplines also contribute actively to the debate. Of the 247 articles included in this review, the only identified contribution published in an IS journal was the article by Gal et al. [2008]. This illustrates the limited focus on BIM-related topics in IS research to date. Yet, as will be presented, the findings from the review show influences from IS research in several areas.

Communications of the Association for Information Systems

Table 3: Journal Frequency Analysis		
Rank	Journal title (Publisher)	Frequency
1	*Automation in Construction* (Elsevier)	49
2	*Journal of Information Technology in Construction* (CIB)	39
3	*Journal of Computing in Civil Engineering* (ASCE)	9
3	*Journal of Construction Engineering & Management* (ASCE)	9
5	*Military Engineer* (SAME)	8
6	EC and M: *Electrical Construction and Maintenance*	6
6	*Tunnelling and Underground Space Technology* (Elsevier)	6
8	*Computers and Geosciences* (Elsevier)	5
8	*Engineering, Construction and Architectural Management* (Emerald)	5
8	*Advanced Engineering Informatics* (Elsevier)	5
8	*Construction Management & Economics* (Taylor & Francis Group)	5
12	*Engineering Structures* (Elsevier)	4
12	*Advances in Engineering Software* (Elsevier)	4
12	*Modern Steel Construction* (AISC)	4
12	*Tsinghua Science and Technology* (Tsinghua University)	4
16	*Canadian Journal of Civil Engineering* (Canadian Society for Civil Engineering)	3
16	*Jianzhu Jiegou Xuebao / Journal of Building Structures*	3
16	*Yanshilixue Yu Gongcheng Xuebao / Chinese Journal of Rock Mechanics and Engineering*	3
19	*International Journal of Design Sciences and Technology* (EUROPIA)	2
19	*Architectural Engineering and Design Management* (CIB)	2
34	*European Journal of Information Systems* (Palgrave)	1

Categories of BIM Research

The articles on BIM topics were classified into subcategories of construction informatics by using Turk's framework (Table 1). If an article covered more than one topic, it was classified into the category perceived as predominant. Table 4 shows the result of classifying the articles into the themes. Most articles focus on processing topics. This finding corroborates former research stating that research within CI is largely focused on technological advancements [Amor, 2002; Björk, 1999]. In what follows, the main characteristics of the research work found within the topic areas are addressed. Further, we point out examples of how several of these areas have a clear overlap with IS research.

Table 4: Classification of Research Themes in Construction Informatics		
Category	No. of articles	Percentage
Common infrastructures	16	6,1%
Communication and coordination	22	8,3%
Processing	115	43,6%
Deployment	38	14,4%
Impact	42	15,8%
Needs	15	5,7%
Transfer	16	6,1%

Core Themes of BIM Research

This section presents an overview of BIM-related research within the core themes in Turk's framework. Turk [2006, 2007] argues that the core themes address foremost construction specific ICT development issues, with the focus reflecting the strong technical orientation of the AEC industry. We present brief examples of representative research in each of the core theme categories of common infrastructures, communication, and coordination and processing.

Common Infrastructures

The research classified within this topic area focuses on common technical, social, and legal infrastructures required to interconnect computers and users to enable BIM. There is a wide range of infrastructure-related problems addressed within the articles classified. With the gradually increasing industry-wide diffusion of BIM technology, the importance of effective common infrastructures within and between organizations increases. To enable these infrastructures for BIM technology use, the construction industry has to cope with a variety of technical, managerial, cultural, and socio/political challenges [Ahuja, Yang, and Shankar, 2009]. Researchers argue that firms need to rethink common knowledge management, legal, and contractual aspects of ICT, quality and performance, total lifecycle information management, and human aspects in order to enable BIM [Rezgui and Zarli, 2006]. The following paragraph reflects on some of the articles to provide a brief understanding of the ongoing debate.

Firms in the construction industry exist along a spectrum from large, highly computer-literate firms to small firms that hardly use computers in their work. Likewise, existing ICT infrastructures and the challenges for firms on their way to enable BIM differ significantly. This is reflected in the literature, including both studies on large firms and their need to improve ICT for inter-enterprise information exchange in multinational construction settings [Kazi and Charoenngam, 2003; Klinc, Turk, and Dolenc, 2010] and of small firms operating in developing countries [Ahuja et al., 2009]. Moreover, the required ICT skills of individual design team members for effective work with BIM technology are subject to discussion [Sher, Sherratt, Williams, and Gameson, 2009]. Some researchers focus on legal uncertainties associated with using BIM and argue that lawmakers need to adjust contractual standards for information exchange. Several reasons for these uncertainties have been identified: "a lack of contractual standards around the 3D model, process complexities that are deeply embedded in practice conventions, along with legal constraints and risk allocation, pose challenges to the establishment of standard agreements" [Ku and Pollalis, 2009, p. 366]. Overall, it can be concluded that technical and legal infrastructure issues are widely debated and thus persistent topics within BIM research. The challenges of establishing common infrastructures are also focused in several areas of IS research, such as IT integration [Singletary and Watson, 2003], enterprise integration [Lam, 2004], knowledge integration [Mitchell, 2006], and information infrastructures [Bygstad, 2010].

Communication and Coordination

The articles classified in this theme category address the integration of BIM technology and various enterprise systems. Further, the use of BIM to advance automation in construction is debated. Also, BIM and its effect on interpersonal interaction is subject to discussion in this topic area.

Researchers within this area debate if and how the utility of BIM can be increased by further integration with enterprise systems like ERP [Babič, Podbreznik, and Robolj, 2010], estimating software packages [Shen and Issa, 2010] and databases for project cost information [Carroll, 2007]. Additionally, it is discussed whether the implementation of BIM under the cloud computing paradigm might be a feasible solution for small firms with limited budgets for ICT investments [Jardim-Goncalves and Grilo, 2010, 2011]. Some research addresses BIM and its use for Automation and robotics in the construction industry. A topic discussed is how Radio Frequency Identification (RFID) tags, readers, and software, which are currently employed by the construction industry to mark and track construction material, could be integrated with BIM software. This functionality might ease construction management tasks as the real-time availability of material can be simulated in the virtual building model [Motamedi and Hammad, 2009]. Similarly, the opportunities and potential impact of emerging technologies such as cloud computing and RFID are being addressed in IS research (e.g., Iyer and Henderson, 2010; Kamoun, 2008).

Processing

The articles classified in this area address the creation, management, publishing, and retrieval of BIM data. The research within this topic area accounts for over 40 percent of the articles included in the review. Due to the scope of this research, this category has been further divided into three subtopics, based on Turk's framework. These are: (1) computationally and knowledge intensive applications, (2) modeling and drafting, and (3) database and knowledge management.

1. Computationally and knowledge intensive applications—Virtual design technologies open new opportunities for designers to simulate and analyze a building's functionality. Advanced software tools to develop and analyze virtual models aid construction designers' precision in resolving technical design tasks. The research in this area is largely contributed by the various engineering disciplines involved in the AEC industry (geotechnical, structural, electrical, heating ventilation and air-conditioning (HVAC), plumbing), discussing the BIM applications relevant for their field of expertise. Within this subcategory, we find the following main research streams: integration of BIM and Geographical Information Systems (GIS) [de Rienzo, Oreste, and Pelizza, 2008], BIM and Finite Elements Method (FEM) software in structural engineering [Casolo, 2009], and BIM and software to predict ground movements in tunneling [Franzius, Potts, and Burland, 2005]. Such simulations are of high practical value in earthquake design, bridge design, fire simulations, for simulations of air movements, ground movements, and basically any kind of dynamic movements and other external forces affecting a building. The articles report advancement in engineering knowledge related to BIM technologies. The majority of articles identified in this area are of a techno-centric nature. This subtopic is the largest single area identified in terms of number of articles in the literature review sample.
2. Modeling and drafting—The maturation of digital information exchange continues to be a widely debated topic in the BIM research agenda. Exchange formats like the Industry Foundation Classes (IFC) are available and in use but not yet fully functional for all parties in the construction project [Lighthart, 2010]. Especially the wide range of software tools, data models, and file formats hinder effective information exchange in concurrent design. Common data exchange standards include IFC, Standard for the Exchange of Product model data (STEP), and Extensible Markup Language (XML). To tackle the problem of

interoperability, research suggests the use of so-called “project information delivery manuals” (IDM) where data exchange standards are agreed upon at project initiation [Eastman, Jeong, Sacks and Kaner, 2010]. Others argue that the “extremely document centric” [Isikdag and Underwood, 2010b, p. 545] nature of the AEC industry requires effective storage and exchange mechanisms for data exchange and suggest the use of so-called design patterns to guide and establish a BIM-based collaborative environment [Isikdag and Underwood, 2010b]. Overall, it can be concluded that interoperability issues are widely discussed and persistent topics in BIM research. Similarly, interoperability and evolving standards are recurring issues in IS research [Nakatani, Chuang, and Zhou, 2006], e.g., in the domain of healthcare information systems [Spil, Katsma, and Stegwee, 2007].

3. Databases and knowledge management—Knowledge may be a company’s most important competitive asset, and research begins to appreciate the importance of knowledge management for the AEC industry [Williams, 2007]. Historically, the construction industry relies to a large extent on the expertise of subject-matter experts, and their knowledge has typically been lost when these experts leave the company [Williams, 2007]. The articles classified in this topic area discuss the specific challenges of knowledge capture and sharing in the project-based construction industry [Bigliardi, Dormio, and Galati, 2010]. Further, researchers debate how virtual design technologies could aid knowledge management and information retrieval. It is debated how tacit construction knowledge could be embedded in BIM software. Some researchers recommend making BIM software more intelligent by developing so-called “smart AEC objects” [Halfawy and Froese, 2005]. AEC objects are parametric objects representing, for instance, single wall units within the BIM software, and making these entities smart includes linking practical construction knowledge to these objects. This practice makes tacit construction knowledge available for designers and other participants using the software. BIM technology offers new prospects for keeping construction knowledge within the firms [Lee, Sacks, and Eastman, 2006]. A second approach to BIM-enabled knowledge management is the development of so-called product libraries for e-procurement, keeping historical construction cost and product data knowledge within the firms [Ajam, Alshawi, and Mezher, 2010; Gangwar and McCoy, 2008; Grilo and Jardim-Goncalves, 2011; Nour, 2010]. The limited number of articles identified in this subcategory indicates a need for more research on BIM-related content and knowledge management in construction organizations. The body of IS research on knowledge management [Alavi and Leidner, 2001] and enterprise content management [Grahlman, Helms, Hilhorst, Brinkkemper and van Amerongen, 2012] here represents a natural foundation.

Support Themes of BIM Research

Within the framework, support themes are defined as topics where CI research could benefit from knowledge transferred from other research disciplines [Turk, 2006, 2007]. The issues debated include the deployment of BIM technology, its impact on organizational practice, the agendas set for further research, and BIM in education and training.

Deployment

A considerable interest in research related to the adoption of BIM technologies could be identified, including a wide range of different dimensions and topics. The research differs in level of analysis and spans from industry-wide to organizational adoption of BIM. Moreover, the research focus comprises a wide range of adoption issues, including the assessment of industry-wide BIM adoption rates, evaluation of organizational benefits, discussion of adoption barriers, development of implementation strategies, and assessment of organizational BIM adoption maturity. The articles express a common agreement that the construction industry is facing large structural difficulties, hindering the sharing of information, integrated construction processes, and, therefore, the adoption of BIM technology. Frequently mentioned structural difficulties in the AEC industry include a lack of knowledge about the possibilities of ICT, the fragmented nature of the industry and the slow development of common data exchange practices [Howard and Björk, 2010]. The necessity for construction organizations to adopt BIM technology is debated in research, and both the benefits and drawbacks of BIM technology adoption receive attention. Research seeking to analyze and identify the benefits of BIM adoption for construction design [Khanzode, Fischer, and Reed, 2008] and research discussing the barriers of BIM adoption could be identified [Peansupap and Walker, 2006]. Further, researchers discuss the influence of individual project situations, company size, and IT literacy on the appropriateness of BIM technology adoption. A framework designed to assess construction firms’ readiness for BIM adoption in terms of IT competence and experience is presented by Succar [2009]. Many construction executives are critical towards BIM technology adoption and doubt that BIM systems can deliver the promised value for their construction projects. In this respect, research addressing the perceived usefulness of BIM technologies in AEC organizations is undertaken [Kubicki, Guerriero, and Johannsen, 2009; Suermann and Issa, 2009]. The authors report that BIM is perceived by practitioners as most useful to improve a building’s quality, the timely completion of the building, and a reduction of working-hours required to create the building.

The practical side of implementing BIM technology in construction organizations is also the focus of several studies. An example of this research is the studies by Peansupap and Walker [2005, 2006a, 2006b], seeking to explain intra-organizational BIM adoption by applying the technological diffusion approach [Cooper and Zmud, 1990] to the construction setting. However, BIM is ICT used for the purpose of inter-organizational communication and collaboration, and, therefore, implementation frameworks need to acknowledge its nature as a shared system used by multiple project partners. Research developing theoretical frameworks to explain inter-organizational phenomena emerging in BIM adoption has been presented, based on the boundary object lens [Gal et al., 2008; Neff, Fiore-Silfvast, and Dossick, 2010]. Moreover, Actor Network Theory (ANT) has been deployed to explain the behavior of the various actors in BIM adoption [Linderoth, 2010]. Also, the possible outcomes of BIM adoption are debated. Topics studied include the interrelationship of BIM and corporate innovation processes [Rankin and Luther, 2006], and how BIM technology affects the collaboration of specialist designers [Dossick and Neff, 2010]. Finally, user adoption and especially how users might drive innovation and ICT adoption in the building process are discussed [Christiansson, Sørensen, Rødtness, Abrahamsen, Riemnann, and Alsdorf , 2008; Sørensen, Christiansson, and Svidt, 2009]. Overall, the Deployment category covers topics that go to the core of IS research, related to factors influencing ICT adoption and use at the user, organizational, and inter-organizational level [Nevo et al., 2009].

Impact

With increasing adoption of BIM, several intended and unintended impacts begin to materialize and change industrial practice. Researchers study how BIM technology impacts the economic, environmental, social, and safety performance of construction organizations. The debate includes evaluations of the impact and how it differs from expectations at the outset, with specific focus on the impact of BIM on construction scheduling, construction estimation, sustainability issues, and lean construction practices.

Early on in the evolution of BIM technologies, researchers recognized the potential of these technologies to improve construction scheduling. Early work on this topic discussed the possibilities to link construction schedules and virtual models to simulate how construction projects evolve over time [Colliers and Fischer, 1996]. In the late 1990s, the term *4D CAD* was coined to describe applications combining BIM and scheduling functionality. Today 4D applications have matured to a stage where they are commercially available and users are able to view simulations of their project schedule. Early adopters of 4D technology are foremost large construction firms comfortable in using advanced computer applications. In this respect, recent research studies the scheduling accuracy in large construction firms, such as Hochtief AG and Turner Construction, to understand the practical benefits of 4D technology usage [Hartmann, Gao, and Fischer, 2008]. With maturing 4D CAD applications, research debates if their utility could be increased further by linking the 4D animated schedules to costing information. Virtual modeling applications linking cost estimates, scheduling functions, and the BIM model are commonly referred to as 5D CAD. Today, the first 5D CAD programs in the form of add-on modules for 3D CAD are commercially available. The underlying logic of these programs is to link every object in the BIM model to a costing recipe. These recipes describe labor, material, equipment, and plant required to produce the object. The costing information is especially helpful to assess design alternatives and their financial consequences. Researchers currently study whether BIM-enabled 5D technology is superior to traditional estimation methods [Shen and Issa, 2010].

Another research stream debates how BIM technology impacts on-site construction and whether this technology aids “leaner” and more industrialized production processes. Lean construction is a new movement in construction management seeking to adopt the lean manufacturing paradigm to the construction industry. Lean construction champions argue that the use of BIM technology in construction planning can reduce rework and inefficiencies in on-site construction work [Arayici, Coates, Koskela, Kagioglou, Usher, and O'Reilly, 2011; Sacks, Treckmann, and Rozenfeld, 2009; Sacks, Koskela, Dave, and Owen, 2010a; Sacks, Radosavljevic, and Barak, 2010b]. A research stream addressing how BIM-enabled design can impact the “green” performance of buildings was also identified. A building’s CO^2 footprint is determined in its design, and the research focuses how virtual models could be equipped with simulation functionality to increase the designers’ environmental awareness. An example is a research article addressing how BIM software can aid design to fulfill the requirements of the Leadership in Energy and Environmental Design (LEED®) standards [Azhar, Carlton, Olsen, and Ahmad, 2011]. Further, research in this category also studies the socio-cultural impact of BIM technologies in organizations and these researchers argue that BIM technology alters organizational culture and structures in construction firms [Anumba, Dainty, Ison, Sergeant, 2006] and affects the users’ daily work practices [Aziz, Anumba, and Peña-Mora, 2009]. BIM might change the nature of the user community, their processes and practices, as well as other structural factors that relate to the people using them [Anumba et al., 2006]. Last, several papers discuss the prospective improvements which BIM technology might yield for construction site safety [Bansal, 2011]. The Impact category can be seen as parallel to the well-developed body of research on evaluation of IS impact, covering a range of evaluation perspectives and methods [Irani and Love, 2001].

Needs

Several articles establishing roadmaps for further BIM research were identified within this category. An example of this work is a recent paper by Owen et al. [2010], highlighting the need for further "… skill development, process reengineering, responsive information technology, enhanced interoperability and integrating knowledge management" (p. 232) in the construction industry. They further claim that while BIM now has been fairly widely adopted, foremost it is used analogously to the former 2D CAD tools, replicating current processes. Isikdag Underwood, Kuruoglu, Goulding, and Acikalin [2009] discuss further directions for construction informatics, pointing out the "inevitable need" for studies to explore BIM's potential to change the industry's organizational processes and practices. They continue by stating that research focused on strategic ICT management and process change is essential to inform organizations prior to the investments in ICT about the consequences of their actions. However, they argue that construction ICT R&D in general suffers from a lack of funding and educated scholars. Examples of research seeking to generate an overview of contemporary BIM R&D have been presented earlier in this article (e.g., Table 2) [Isikdag and Underwood, 2010a].

Transfer

The articles classified within this category discuss how BIM-related techniques should be incorporated in architectural and engineering education and what the curricula should include. An example is the article by Peterson, Hartmann, Fruchter and Fischer [2011] discussing how BIM should be integrated in construction management programs at the universities. In a similar vein, Zhu, Zhang, and Ahmad [2010] discuss the importance of improving multidisciplinary communication skills of students in AEC education programs by using ICT to facilitate teaching and learning.

V. DISCUSSION AND IMPLICATIONS

As presented in this review, the research on BIM spans a wide range of topics of which several would seem familiar to IS researchers. While IS already can be regarded to serve as a reference discipline for some of the BIM research, this is seldom explicitly acknowledged. We have also identified several areas where we argue that a stronger influence from IS would contribute to bring the knowledge further, and that represents interesting potential for IS research. In the following we discuss these areas related to the core and support themes from the review.

Core Themes

The majority of studies classified as core themes seek to explore how the functional affordance of BIM can be improved to make it a better technology for its users and help them to achieve their goals. Functional affordance is here defined as "a relationship between a technical object and a user group that identifies what the user may be able to do with the object, given the user's capabilities and goals" [Markus and Silver, 2008, p. 622]. For instance, the literature classified in the "processing" category accounts for over 40 percent of all articles reviewed. Inspired by limitations observed in current design practice, the authors discuss what the technology should afford to best fulfill the needs of BIM users in different AEC disciplines. Likewise, the literature in the other core topics "common infrastructures" and "communication and coordination" seeks to explore what BIM technology should be able to afford considering existing information infrastructures and enterprise systems (e.g., ERP, databases). The core topic literature discusses construction-specific BIM development topics, and we found the work to be guided by a strong focus on functional affordance. We argue that BIM research is in need of a broader perspective fusing "functional affordance" and "human agency" to explain how well BIM serves the users' goals. We argue that this limitation of current work offers a possibility for IS research to contribute, based on former work on materialism and agency and previous work studying the intertwined and at times conflicting nature of technical affordance and human agency such as the "imbrication analysis" approach [Leonardi, 2011; Orlikowski and Barley, 2001].

Support Themes

Several of the research themes in this category fall within the scope of IS, such as BIM research discussing the deployment of BIM in groups, organizations and the AEC industry, and BIM research seeking to explain and facilitate the potential impact of BIM on organizations in the construction industry. Theories and models frequently used in IS research, such as the technology acceptance model (TAM) [Davis, 1989], diffusion of innovations [Fichman, 2000], ANT [Walsham, 1997], and boundary objects [Levina and Vaast, 2005] are also applied in BIM deployment research. In the literature on BIM deployment, we found examples of scholars beginning to study how technical details of BIM are linked to a "larger and more general view of the sociological nature of communication, coordination and knowledge creation" [Baxter, 2008, pp. 81–82]. In this respect, researchers have conceptualized BIM as a boundary object or undertake studies guided by actor network theory, seeking to study the "fluent patterns linking CAD to its sociological impact" [Baxter, 2008]. However, this perspective is just emerging in BIM research, as we found only a few articles taking this theoretical stance [Gal et al., 2008; Linderoth, 2010]. Building Information Models serve as design spaces where collaborative dialogue among the parties in a construction project takes place. Considering BIM's role to facilitate such dialogue, in conjunction with our finding that current BIM research sparsely addresses the linkage of technical and social aspects, we argue that BIM research needs to be strengthened in this respect. While several researchers in CSCW and Participatory Design conduct work related to this [Christensen, 2007; Safin et al., 2010; Schmidt and Wagner, 2004; Tory et al., 2008; Wagner, 2010], there is yet little attention to this topic in the mainstream IS journals. Further IS research on BIM's role in collaboration could be informed by the inter-organizational information systems literature [Robey, Im, and Wareham, 2008].

When studying the deployment literature, we further found that only few studies recognized the multifaceted relationship between organizational culture and BIM [Anumba et al., 2006; Gal et al., 2008]. However, "the practices and identity of each organization are reciprocally shaped" [Gal et al., 2008, p. 292] when organizations use shared information technology, and we argue that the link between BIM and organizational culture is understudied in current BIM deployment literature. Moreover, tensions arising from "distinct organizational backgrounds" [Gal et al., 2008, p. 290] and a lack of fit between the actors' organizational cultures (e.g., architects, contractors) may cause conflicts which negatively affect the way in which the actors communicate in construction projects. IS researchers could strengthen BIM research in this respect based on former studies on IT and organizational culture [Leidner and Kayworth, 2006].

Much of the literature studying BIM's organizational impact is inspired by automation and rationalization considerations (e.g. automation of design tasks, supporting cost estimation, or time scheduling) and could be characterized by the technological imperative perspective dominant in early IS research [Markus and Robey, 1988]. We found little discussion about BIM's potential role as a strategic asset to transform an organization. In this respect, the focus on optimization of existing processes rather than redesign reflects an untapped potential similar to what was pointed out in the early reengineering literature [Hammer, 1990]. Our review thus supports the argument that BIM's "transformational capability" to revolutionize and change the way in which AEC organizations do business has yet to be understood [Ahmad and Sein, 2008, 2010; Isikdag et al., 2009]. The identified need for more research on the strategic potential and implications of BIM implementation in construction projects thus represents an interesting opportunity for IS researchers to contribute, based on former research on the strategic potential of other ICT innovations (e.g., Henderson and Venkatraman, 1999; Luftman, 2003; Rivard, Raymond, and Verreault, 2006; Venkatraman, 2005) and IT-driven organizational change [Markus, 2004].

Last, we found only a few articles seeking to measure BIM's business value. The unit of analysis in these studies was limited to studying first-order effects such as BIM's impact on scheduling or cost estimation accuracy. We argue that IS evaluation research based on techniques such as balanced scorecard, benchmarking, or post implementation reviews should be applied to understand BIM's actual business value. This represents an interesting opportunity for IS researchers to contribute based on earlier work on IT and organizational performance (e.g., DeLone and McLean, 2003; Melville, Kraemer, and Gurbaxani, 2004).

In this discussion we have highlighted several areas for further research. Given the increasing interest in this topic area, IS researchers are advised to closely monitor further developments through conducting regular literature reviews. There are several aspects on which the review procedure applied in this article could be extended. First, it would be possible to conduct backward and forward searches based on the identified articles [vom Brocke et al., 2009]. Second, further studies could replicate our study using other publication databases. Third, researchers interested in specific sub-topics should deploy key word combinations allowing them to identify smaller and more focused samples, which might provide insights useful to complement our results.

VI. CONCLUSIONS

Based on a systematic review of journal publications on Building Information Modeling, this article has provided an overview of the nature and scope of the research conducted in this domain to date. Our analysis shows that IS to some extent serves as a reference discipline and that theories used in IS research are also informing contemporary BIM research. We also identified a few examples of BIM-related research within IS, which provides a useful basis for further research in this area. Our main intent in this article has been to suggest what might be gained by strengthening the IS contribution in BIM research, and we have pointed to several limitations in current BIM literature which represent research avenues worthwhile pursuing for IS researchers. Based on this, the following areas in need of further IS research were identified: studies on the relationship between BIM's functional affordance and human agency, adoption and use of BIM for inter-organizational collaboration, the influence of organizational culture on BIM practices, the capabilities of BIM for transforming industry practice, and identifying the business value of BIM. As pointed out in the discussion, there is a well-established knowledge base in IS research that can be drawn upon for studying these issues. This, combined with the exciting potential of BIM for transforming a major industry such as building construction, leads us to conclude that BIM is an area ripe for IS research.

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Editor's Note: The following reference list contains hyperlinks to World Wide Web pages. Readers who have the ability to access the Web directly from their word processor or are reading the article on the Web, can gain direct access to these linked references. Readers are warned, however, that:

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UNORCHESTRATED SYMPHONY: THE CASE OF INTER-ORGANIZATIONAL COLLABORATION IN DIGITAL CONSTRUCTION DESIGN

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SUMMARY: *This paper presents the findings from a study of collaborative work among design professionals in virtual modeling for building construction. The research is based on interviews conducted with members from various design professions. We analyzed a building project comprising a network of organizations interrelated by their information systems, to gain a better understanding of collaborative design based on Building Information Modeling (BIM). The findings suggest that the actors did not fully exploit the capability of BIM to transform and improve project communication, as they did not adjust the inter-organizational processes according to the BIM technology. Instead of effective collaboration, we found a system of "automation islands." To achieve full business-process integration, the actors would need to establish a shared organizing vision for BIM. This organizing vision needs to align inter-organizational processes and the functionality of BIM. Our findings illustrate weaknesses in existing practice and highlight possible improvements.*

KEYWORDS: *building information modeling, construction project, digital design, inter-organizational systems, collaboration, configuration analysis, case study*

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1. INTRODUCTION

It is widely accepted that Information and Communication Technology (ICT) promotes efficiency in communication and has the potential to change the way in which organizations in the Architecture, Engineering and Construction (AEC) industry interact. In this respect, organizations in the AEC industry gradually substitute their traditional, paper-based, two-dimensional (2D) Computer Aided Design (CAD) tools for three-dimensional (3D) technologies. These technologies, commonly referred to as Building Information Modeling (BIM), are digital representations of all physical and functional characteristics of a facility (NIBS, 2007). Moreover, BIM is intended to serve as a design space where multiple actors engage in collaborative dialogue. Ideally, the result of such dialogue is a common virtual building model created through a joint effort and close collaboration, with all the actors providing designs for the construction project. In this respect, there is a need for actors to coordinate design activities and to synchronize their cooperative activities toward working within a shared information system.

Innovative, ICT-supported practices, including BIM, can serve as a catalyst for firm performance and innovation (Baxter and Berente, 2010). In this respect, numerous scholars have discussed the opportunities of BIM to advance transparency, visualization, and clarity in construction design information sharing (Khanzode et al, 2008). However, to attain the anticipated IT-enabled benefits, actors need to substitute their old design technology with the new technology, and transform structures, and processes within, and across the participating organizations.

BIM's potential to transform or even revolutionize collaborative work in construction design is, however, frequently left untapped (Ahmad and Sein, 2008; Ahmad et al, 2010). Scholars argue that collaborative design using a shared information system such as BIM is virtually impossible without changing the actors' traditional working processes and routines (Owen et al, 2010). They see multiple hurdles for the free flow of information and intelligence across organizational boundaries. Especially the root characteristics of the AEC industry such as a high division of labor, cost consciousness, little institutional leadership, and a lack of standards in technology and business models seem to impair effective collaboration (Peansupap and Walker, 2006; Rankin et al, 2006). In addition, the document-based nature of traditional information exchange, actors' traditional mindsets, their "silo" mentalities and cultures, tensions arising from conflicting organizational interests, and their distinct organizational backgrounds impair effective collaboration in construction design (Gal et al, 2008; Rankin et al, 2006). Moreover, the use of a shared information system is governed by power resource dependencies, individual actor's ICT capabilities, and the significance attributed to the technology by the actors (Lyytinen and Damsgaard, 2011). Thus, finding a common modus operandi for BIM requires that actors deal with a variety of challenges stemming from historically developed structures and processes.

The study presented in this paper is motivated by a recent literature review calling for research into ICT collaboration methodologies for the construction industry and the need for fresh approaches to study digital design practices in construction projects (Shen et al., 2010; Whyte, 2011). We seek to contribute to the understanding of the alignment of strategies and structural arrangements toward BIM, and how these influence design, and information sharing in multi-actor collaboration. Thus, our research is guided by the following question:

How can we analyze the use of BIM for integration in multi-actor digital construction design, to identify challenges and improvements in related practices?

To address this question, we present the results of a case study conducted in a Norwegian construction project, analyzing how the multiple actors organized and used BIM in their project. The theoretical lens guiding the data collection and analysis is the configuration analysis framework (Lyytinen and Damsgaard, 2011). Configuration analysis is an approach employed to gain an understanding of ICT-enabled integration and communication at the inter-organizational level. The intended contribution of this paper is twofold: first, we argue that research taking a configuration analysis perspective can broaden the theoretical understanding of the structural arrangements and strategies governing organizational actors' interaction in digital construction design. Second, the practical contribution of this paper is to showcase how a configuration analysis approach can be of use in identifying the required changes needed to adopt and make use of BIM to achieve improved collaboration in design and construction projects.

The organization of the paper is as follows. Section two presents the theoretical perspective supporting the analysis, section three presents the research methodology, section four presents the data analysis, and is followed by a discussion of the results. Section six presents conclusions and implications.

2. THEORETICAL LENS

In contemporary literature on BIM adoption and use, we find multiple studies theoretically ingrained in ICT diffusion theory, focusing largely on the behavior of single adopters of BIM (Peansupap and Walker, 2006). In addition, we find studies based on the Technology Acceptance Model (TAM), the Theory of Planned Behavior (TPB), and the Unified Theory of Acceptance and Use of Technology (UTAUT), which seek to explain the behavior of multiple single actors (Adriaanse et al, 2009). In more recent work, the focus has shifted toward studying networks of organizations, for example, based on Actor Network Theory (ANT) and Boundary Object Theory (Gal et al, 2008; Jacobsson and Linderoth, 2010; Linderoth, 2010; Whyte and Lobo, 2010). These studies report that a variety of contextual factors (e.g. the project's mode of organizing, contracts, fees for delays, etc.) govern BIM`s rate of utilization and functionality in construction design. Further, the "Design Process Communication Methodology" (DPCM) has been developed based on ideas stemming from Business Process Modeling (BPM), Human Computer Interaction (HCI), and organizational science (Senescu et al, 2011). This methodology seeks to lay the foundation for communication-facilitating software that is useful for the visualization of the communication processes involved in construction projects. Scholars have begun to study how the technical details of BIM are linked to a "larger and more general view of the sociological nature of communication, coordination and knowledge creation" (Baxter, 2008, pp. 81–82). In this respect, a recent paper in ITcon argues that the actors' organizational attitudes, behaviors, and cultures shape the way in which organizations interact (Brewer and Gajendram, 2011). In addition, a further ITcon paper highlights how BIM might impact organizational structures in AEC firms (Oluwole, 2010). Our work can be positioned within the multi-actor-level studies and our paper intends to document how the theoretical lens of configuration analysis contributes to a more in-depth understanding of the collaboration process in BIM design.

The configuration analysis perspective is rooted in organizational theory, where organizations and markets are defined as interconnected structures (Williamson, 1979). The key idea of the configuration analysis is to study a "family" of organizations that are interrelated by their information systems. The authors introduce a set of key parameters, which are briefly presented in the following: Firstly, the parameter *organizing vision* addresses the aims and functionality of an Inter-Organizational Information System (IOIS), which should be agreed upon through the creation of a shared organizational vision. Secondly, *key functionality* defines the scope and content of the data exchanged. Thirdly, the *structure* parameter seeks to describe the roles that organizational actors take in facilitating the inter-organizational information exchange. Fourthly, *mode of interaction* is a measure seeking to describe whether equal relationships between the actors exist, or if obligatory or hierarchical relationships are evident. Lastly, the parameter mode of *appropriation* addresses actors' varying appropriations of technology (Lyytinen and Damsgaard, 2011). The aim of our analysis is to bring about an altered understanding of how interaction in construction projects happens or why it happens as it happens. Table 1, by Lyytinen and Damsgaard (2011), provides an overview of the key elements that constitute an adopter configuration.

TABLE 1: Key elements of an adopter configuration (Lyytinen and Damsgaard, 2011)

Adopter configuration element	Definition
Organizing vision	Conveys a persuasive cognitive model of how the IOIS helps to organize better inter-organizational structures and processes
Key functionality	Defines, in turn, the scope and content of data exchanges and related business functionality in terms of the content of messages, their choreography, and coverage
Structure	Defines the volume of structural relationships between the participating organizations, as defined by the IOIS
Mode of interaction	Nature of relationships between the participating organizations, as defined by the IOIS
Mode of appropriation	The scope and intensity of potential effects of adopting the IOIS for the participating organization

3. METHOD

The setting for our case study is a wood frame, multi-story, low-energy housing development in Norway. The project includes the construction of three apartment buildings altogether consisting of one hundred individual apartment units. The project has been chosen based on several selection criteria. The first criterion was that the projects' participants should resemble a rather typical project constellation in the industry (e.g. client, architect, contractor, HVAC designer, structural engineer, electrical designer). The second criterion was that digital modeling technology had to be in use in the project's design stage. The last criterion was to choose a project that had neared the completion of the design phase. The chosen project fulfilled all of the aforementioned criteria. The data collection was undertaken during the final design stage of the project. Most of the organizations subject to our case study were located in Norway, with five in the same city, and one in a different region of Norway, while the structural timber engineering firm was located in Switzerland. Bi-weekly design meetings were held in one of the Norwegian cities where most of the firms were located. The design meetings required firms to send their representatives. No videoconferencing systems or similar support technologies were deployed to facilitate the meetings. This practice precluded some actors, such as the Swiss firm, from regular participation in the project meetings.

Ten semi-structured interviews were conducted with actors involved in the project's design in the period from September 2011 to March 2012. The case project's design was produced by six firms: the architectural office, the timber frame builder, an engineering office producing structural, mechanical, and electrical design components, a geotechnical engineering office, a fire-protection designer, and a specialized structural engineer for timber structures. We decided to interview at least one designer in each firm who actively participated in the project's design. We collected data from interviews with project managers, designers who were working hands on with the technology, and firms' CEOs. A detailed overview of the modalities of the interviews—that is, the persons interviewed, the interviewing technique applied, and the design services provided by the actors—can be found in Table 2. Four of the interviews were conducted face-to-face at the firms' branch offices and six were conducted through Skype. Each interview lasted approximately one hour. The chosen interviewing strategy allowed us to capture the on-going design interaction in the case project in its full breadth. After the interviews, we provided the participants with a transcript of our article, and called the interviewees thereafter to briefly discuss, and clarify our findings. The respondents agreed overall with our interpretations, and we considered critical comments, and improved our work by filling "holes" through close collaboration with the practitioners. We argue that this procedure of member validation added to the plausibility and validity of the findings presented in this article (Bygstad and Munkvold, 2011).

TABLE 2: Interviews conducted

Person interviewed	Services provided	Interview technique
Timber frame builder, design manager	Design, production, and installation of all wooden components	Face-to-face
Timber frame builder, CEO		
Timber frame builder, drafter		
Timber frame builder, production manager		
Geotechnical engineer	Geotechnical design	Skype
Architect	Architectural design	
Engineering design coordinator (structural, HVAC, and electro)	Structural, electrical, and HVAC design	
Fire-protection engineer	Fire-protection design	
Client, CEO	Client	
Structural engineer (timber frame)	Specialist structural design of wooden components	

The researcher's civil engineering background, comprising both work experience and university level education, helped to minimize the social dissonance between the interviewer and respondents. In addition, the interviewer's background allowed for the mutual use and understanding of construction-specific jargon/language**.** All interviewees were informed beforehand about the modalities of the interviews and gave their informed consent for the process. The interviews were recorded, transcribed, and coded according to the parameters relevant in configuration analysis. The software used to support the coding of the interviews was NVivo 9. The coding was performed by uploading transcripts as documents into NVivo9, assigning nodes to notions that could be related to the key parameters, and creating reports that related the occurrences across interviews.

4. ANALYSIS

The analysis in this paper is based on the configuration analysis approach. We define an adopter configuration as a group or cluster of organizations that are interrelated by their information systems. The elements that constitute the configuration in our case are design systems that allow information to be sent across organizational boundaries. In what follows, we report on which set of organizations assembles the adopter configuration in our case project and we map the information systems linking these organizations. After having established the adopter configuration as a unit of analysis, we present our aggregated data based on the key parameters in configuration analysis; that is, organizing vision, key functionality, structure, mode of interaction, and mode of appropriation.

4.1. The adopter configuration

The adopter configuration forms the unit of analysis for our case study. Our criterion for including organizations in the adopter configuration was their use of design systems. The firms using systems that allowed them to create, transmit, and retrieve virtual models via the Industry Foundation Classes (IFC) file format were considered as part of the adopter configuration. Ergo, the adopter configuration is made up of a set of organizations that had the technical capability to be able to participate in BIM. The adopter configuration of our case project included the following firms: architect, electrical engineer, structural engineer, HVAC engineer, main contractor (timber frame), and the structural engineer (timber frame). The "outliers" of the adopter configuration in the case project were the client, the geotechnical engineer, and the fire-protection designer. These firms did not deploy systems that were useful for active participation in BIM design. The black squares in Figure 1 depict organizational actors being part of the adopter configuration, while those remaining white portray firms that were not technically able to participate in a shared BIM. On the left-hand side in Figure 1, we identified a group of actors—the engineering design coordinator, the electrical, and structural, and HVAC engineers—who were part of a single organization and who had established an internal role as a design coordinator. The lines in Figure 1 represent the project's main communication path throughout the design phase, acknowledging the architect's role as a communication hub.

The organizations in the case project deploy a variety of information systems to facilitate the creation and transmission of design information. These systems allow partners in a network to collaborate by exchanging structured design information across organizational boundaries; they are therefore IOIS (Kumar and van Dissel, 1996). In virtual construction design, each party prepares a specialist model covering their area of expertise. This is reflected by the information systems used in the case project, which are essentially design programs adapted for the special needs of subject-matter experts.

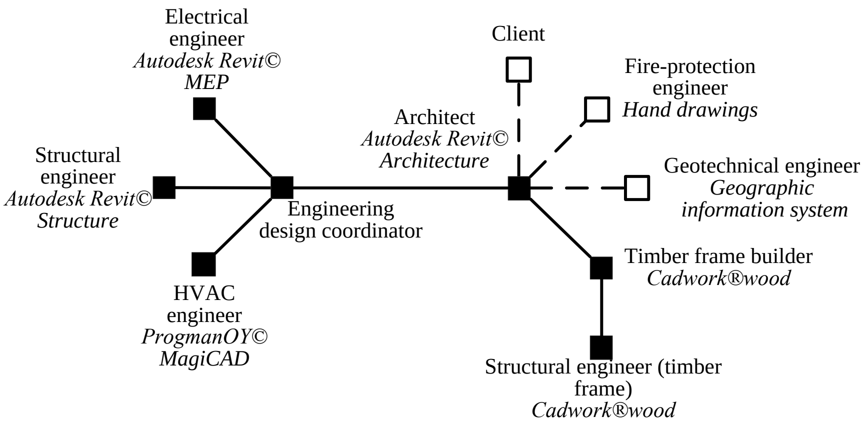


FIG 1. Project configuration

In the case project, the architect designed the project using architectural design software (Autodesk Revit© Architecture). The electrical engineer used software suited for mechanical, electrical, and plumbing engineers (Autodesk Revit©MEP), the structural engineer used software suited for structural design (Autodesk Revit©Structure), and the HVAC designer used software developed for building services (ProgmanOY©MagiCAD). The electrical, structural, and HVAC designers worked for the same firm and they received their modeling information via an internal server. The firms involved in the design of the timber structure used customized software for timber construction (Cadwork®wood). All of the aforementioned programs have in common that they allow for the creation of virtual models that could be joined to a common building model. The geotechnical engineer created a virtual terrain model by using a Geographic Information System (GIS) and, in parallel, they used a 2D drawing system to create their drawings (AutoCad). The CAD system was, however, not designed for the creation of parametric objects. The fire-safety engineers created hand sketches to provide their services. A detailed map of the information systems deployed within the case project can be found in Figure 1.

4.2. Organizing vision

For the functionality of an IOIS such as BIM, it is of critical importance that the actors involved agree on the aims and functions of the IOIS through the development of a shared organizing vision (Lyytinen and Damsgaard, 2011). A shared organizing vision is a cognitive model of how to organize the inter-organizational structures and processes (ibid.).

Specially designed building contracts are regarded by many researchers as an essential means to create a shared organizing vision of BIM. Such contracts could specify, for instance, the role of each participant in the shared system, the role of the model manager, design detail limitations, and could resolve issues related to the intellectual property held in BIM. However, the parties in the case project worked based on traditional design-bid-build contracts. Their contracts did not address the routines of working together in a shared IOIS in any way. The agreed design deliverables were tender documents consisting of 2D drawing packages and the accompanying documentation. The actors had binding dates for the delivery of the tendering documents. The architect stated that in not establishing a strict arrangement surrounding the BIM model, the design collaboration had been convenient for the actors, as they were not forced into rigid working routines:

> "… for this project at this time it is easier to use what is easy to use for the consultants than to force everybody into a specific way of working, which would maybe be strange to them, or where they would not have experience from before." (Architect)

Beyond contractual arrangements, there are other, less formal, means for creating a shared organizing vision towards working in BIM. The instruments used in the case project for aligning the design activity were bi-weekly, design team meetings. These meetings aimed at resolving design issues along the way and actors voiced what design information they would need from which party at what time. According to the architect, these meetings created a dynamic and open communication among the parties involved. Further, the architect stated that these meetings did not create a strict and rigid routine for drawing and collision checking in BIM, but rather allowed for discussing solutions together. However, due to the geographical dispersion, not all the relevant actors were able to attend all of the design meetings. Alternative possibilities for participating in the design meetings such as videoconferences were not available. The architect was quite satisfied by the way in which the project communication was organized, as the manner of communication was left open and was dynamic:

> "I am kind of satisfied because, as I explained, for us and for many, this project was kind of for the first time, so to leave the way to communicate open and dynamic … and in a way we tried that out on the way as we went along … now I am happy not to have been forced into a very strict routine of drawing and collision checking in Revit from the very beginning, and a full BIM kind of design process, and so on." (Architect)

Neither the contractual arrangements, nor the design meetings were deliberately designed to create a shared organizing vision toward working together with BIM. Moreover, our interview data did not provide evidence for the existence of a shared organizing vision of BIM. This finding is supported by actors stating that they did not have any idea about the design tools that other actors had used to create design contributions. Moreover, actors stated that the modalities of design communication had not been up for discussion:

> "I knew what the architects use and I know what we use but what the timber frame contractor uses, I haven't got a clue." (Engineering design coordinator)

> "In my experience, I have only had a talk with one of them [other actors] a few times as to how the communication should be. So, usually, we do not talk about this." (Drafter timber frame builder)

Not all project actors shared the architect's positive opinion about the way in which the project's communication channels were organized. The absence of a shared organizing vision for BIM was perceived by some actors as a hurdle for effective communication. The timber frame builders, for instance, argued that the ill-defined BIM communication resulted in misunderstandings among the actors:

> "I know when we started off with that program we had a lot of intentions but maybe because we are a small company […] but still we are talking of a well-known architectural company … but I find that communication is not defined enough … there have been misunderstandings already, so again it's sort of mailing things back and forth; it's really the same old thing." (CEO, Timber frame builder)

The fire-protection engineer voiced the opinion that inter-organizational arrangements should not be overly complex and demanding. Nevertheless, he stated that the communication in the case project might have benefited from a clearer understanding of how to interact:

> "I have been on projects with much more control, and with much less control, and I have to say that it should not be too demanding and there should not be too many rules. But in … [this project] … we would have benefited maybe from a slightly clearer understanding of how to interact." (Fire-protection engineer)

The engineering design coordinator stated that it would have only taken a little more effort and precision by the actors to align the communication and to make the project a full-blown BIM project. However, they decided not to pursue the alignment of communication routines because they were not sure who was going to pay for the additional work required to run a fully functional BIM system:

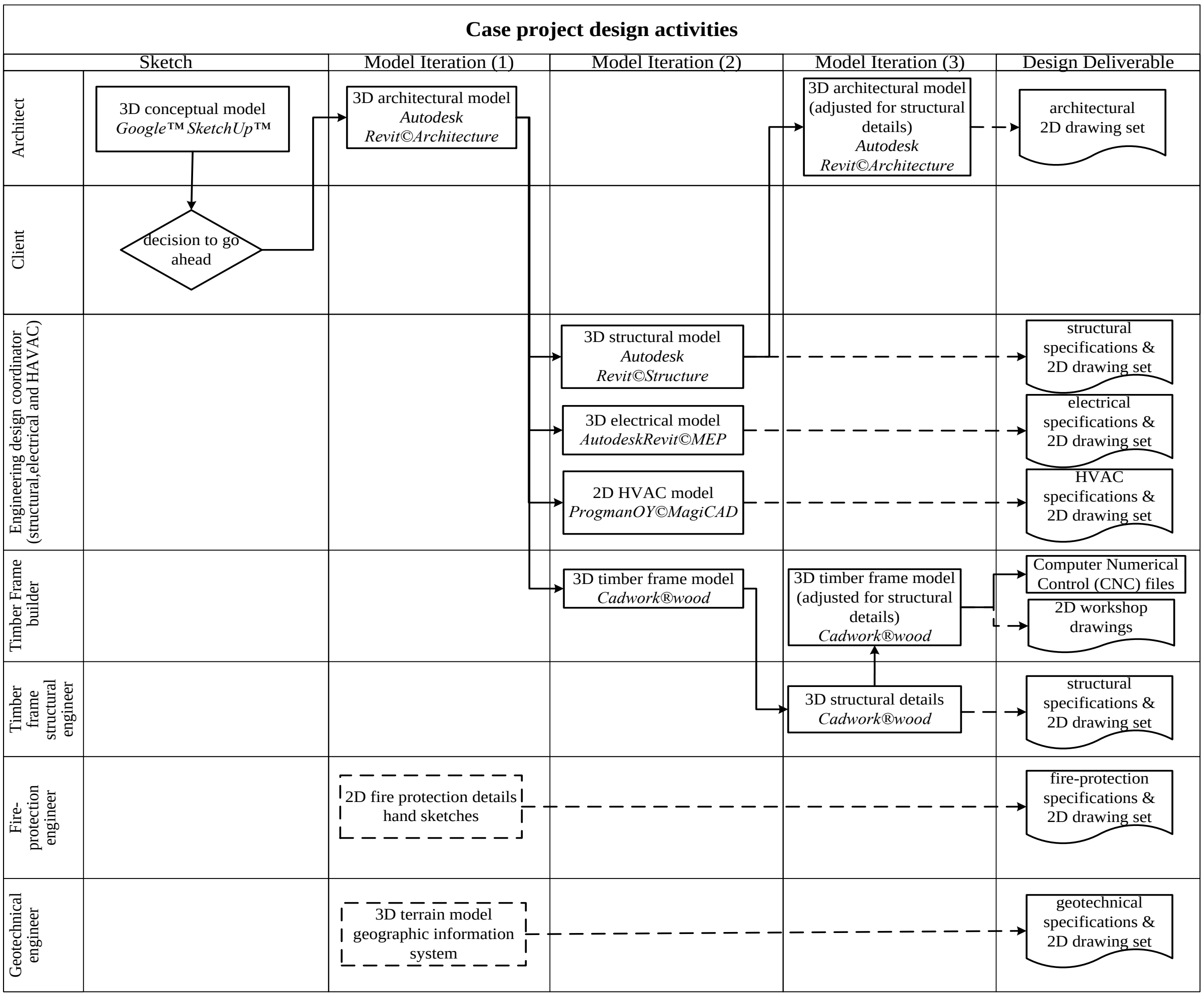
> "It's not that difficult [to run a full BIM], you have to be a little more precise, you need a little more effort. […] The clients have to be willing to pay for the extra work that we do." (Engineering design coordinator)

The parties in the case project did not establish a shared organizing vision for their BIM system. Moreover, no evidence could be found about any efforts that had been undertaken to create such a shared vision. We found that the actors had different opinions about the significance of a shared organizing vision for BIM. Some actors regarded the creation of an organizing vision as counterproductive for free and dynamic project communication (architect). Others regarded the absence of an organizing vision as counterproductive for effective BIM collaboration (timber frame contractor). Some regarded "overly" strict arrangements of inter-organizational processes as counterproductive for information exchange, while acknowledging that some regulations are needed to allow for effective communication (fire-protection engineer). Some actors were concerned about the additional costs for intensified design collaboration (engineering design coordinator).

4.3. Key functionality

The key functionality of an IOIS describes the scope and content of data exchanges and their related business functionality (Lyytinen and Damsgaard, 2011). Therefore, the key functionality of a BIM system, at the inter-organizational level, can be identified by assessing the extent of its usage in facilitating inter-organizational data exchange. Rooted in the interviews taken, we analyzed our case project with the objective in mind of understanding just how much the project communication was shaped by BIM technology. We present our findings by a narration of communication events arranged according to their occurrence throughout the design phases. The chart in Figure 2 presents an overview of the design activities undertaken by the project actors and the software used, encompassing all phases from conceptual design-to-design deliveries onward. The full lines in Figure 2 depict the de facto exchange of modeling data, whereas the dotted lines illustrate occasions of 2D CAD data exchange.

FIG 2. Project design activities



In the early design stages, the architect deployed 3D sketching software to develop and visualize the building's envelope and form (Google™ SketchUp™). These early sketches were used to create a mutual understanding between the client and the architect of what the building would "be like" once completed. The sketches were presented at meetings and formed the basis for discussion. Once the early stage concepts and sketches matured to the stage where they were mutually agreed upon, they served as a foundation for the architectural design. The architect imported the sketching files into the architectural design software that was used from that point on.

The architect deployed architectural design software to create a virtual model of the buildings' shape and outer appearance (Revit® Architecture). Once the buildings' shape and envelope had been completed, the architect plotted the model into IFC files, and transmitted them to the structural engineer, the electrical engineer, the HAVAC designer, and the timber frame builder. The architect produced 2D drawing sets and transmitted them to the fire safety and geotechnical designers, who did not deploy BIM-ready software. The communication between the architect and the other parties concerning the developed model was facilitated by snapshots of the model and hand sketches presented at the design meetings:

> "I used SketchUp to take snapshots of my model and I used, of course, hand drawings and sketches … just in a way to get along, and try to show what we are thinking, and so on. So, it's kind of dynamic, the way we like to do it. It is the fastest way to do it by hand and a quick sketch in a way—for more complex things I would maybe use a SketchUp model as a background for the sketch I make by hand, and so on." (Architect)

The structural engineers used the received architectural model as an envelope for their design work. They imported the received IFC file into their structural design software and used it as an under-layer while creating their own models. The structural designers were experienced BIM users and they did not face any interoperability problems when importing and using the architectural model. Throughout the design process, the structural designers transmitted their models to the architect. The architect incorporated the changes suggested by the structural designers into the architectural model.

However, the majority of the design information between the structural engineer and the other parties was exchanged at the regular design meetings, or via other channels such as mailing back and forth snapshots of their model. Once the structural design had been completed, a 2D drawing package and the accompanying structural calculations were delivered in print and pdf format to both the client and the architect. Like the structural designers, the electrical engineers used the architectural model as a template for their work. The following statement by the engineering design coordinator illustrates that the architectural model was used as an under-layer through which to position the electrical installations:

> "Now we need BIM just as an under-layer as an xref in dwg, etc. We use it to place our components. Find out where we are going to put cables, etc., etc. And, this is then printed out when needed." (Engineering design coordinator)

They had no issues incorporating the architectural model into the electrical design software. However, unlike the structural designers, they did not deliver a completed electrical model back to the architect. The electrical designers used the regular design meetings and mailed back and forth snapshots of their model to align their design work with others. Upon completion of their design, they delivered a 2D drawing package and a list of components to both the client and the architect. The argument for not delivering a model to the other actors was that the lack of complexity in terms of the buildings' electrical design did not require such an exchange:

> "… we haven't been doing that in this project for the technical installations, it's a quite simple project, it is not necessary to do a lot of collision controls because we don't have what you call a large cable routing." (Engineering design coordinator)

The HAVAC designers decided to use architectural 2D drawings instead of the architectural model as the reference frame for their work. The decision to use 2D drawings over 3D models was taken based on the firm's prior experience that working in 2D would require less resources and would be faster than working in 3D. Like the other designers, the HAVAC engineers relied on the design meetings and e-mails to share their design and to receive information concerning integration. When their design was finalized, they submitted a set of drawings, accompanied by building systems' specifications in 2D to both the client and the architect. The argument given for not creating 3D models was that the designers were confident that 2D models would be sufficient for the project:

> "If we just have an ordinary project that is not really complex, and we have a good feeling, then we use MagiCAD because it's much faster to draw with." (Engineering design coordinator)

The timber frame builder was appointed early on in the project due to the owner's preference for using prefabricated wood elements as the main building material. In this respect, the design of the building's shape had to be optimized for the use of prefabricated elements. Therefore, the timber frame builder had a considerably large share of the design activity. Moreover, the decision to execute the project as four-story timber buildings made it necessary to appoint a structural engineer who specialized in timber structures. The timber frame builder's drafter received the architectural design as an IFC file and decided to use just the geometrical information provided in the architectural model. Therefore, they stripped the model of its information by transforming the received IFC file into a Standard ACIS Text (SAT) file, which left nothing but geometrical data behind. The reasons for this practice can be attributed to the actors' differing levels of precision, detail, and foci in terms of the modeling process:

> "I do not know if it's because they [the architect] are not trained enough or if they do not have the right focus, but it seems like always the model is sort of too much [detail] ... there is a lot of rubbish you are not able to use. So, in the end, you sort of only take over the geometry." (CEO, Timber frame builder)

Just as did the other designers, the timber frame builders relied heavily on the information provided in the design meetings. However, their designer was not able to attend to all of the design meetings. The contractors developed a model with the purpose of precisely drafting all of the buildings' wooden components so that they could be machined. They used their model to create Computer Numerical Control (CNC) files, which could be read by their machinery. The timber frame contractors delivered neither their model, nor a set of workshop drawings to any external party other than the structural engineer appointed to handle the timber structure. The structural engineer appointed for assessing the stability of the timber structure, communicated exclusively with the timber frame contractor. After having received the model of the timber components created by the contractor, they returned models of structural details, and a report accompanied by structural calculations to the timber frame contractor. The structural engineer (timber frame) did not participate in any of the project's design meetings, as their firm was located in Switzerland, and the meetings took place in Norway.

The main information exchange was facilitated by traditional means such as meetings, 2D drawing sets, and mailing back and forth snapshots of the models. In support for this, we quote the timber frame construction firm's CEO, who stated that the overall BIM information exchange had been much of the "same old thing," and that it had not worked sufficiently well:

> "Now it feels like it always has been, that somebody might have different models and might have been working on the façade of the building, and they are doing that in SketchUp because that is easier for this, or they write something in a pdf and send that over, and then he is doing his changes to the model, and comes back, and it's not working." (CEO, Timber frame builder)

Several actors opined that the functionality of the project's BIM system might have benefited from a shared BIM server infrastructure, which was not established for the project. However, even though several actors were aware of the importance of such an infrastructure for the BIM system's functionality, no party took the initiative in setting up a BIM server. The following statements show that several actors would have liked to have worked with such a platform, but no party felt responsible enough to actually establish a server:

> "It is normal to use a web hotel to share drawings on the Internet and we have not had it. So, that was some kind of drawback. Often we see that it is the client that in a way demands it or supplies it, that web-hotel solution thing, a server, a system. (Architect)

> "Maybe they [the other participants in the project] should have just made a Revit site in the web where everyone could link in their models. And, everyone could update his information day by day, for instance. And, when someone does a change, one gets notified." (Engineering design coordinator)

> "… as long as people keep on sending things back and forth with e-mails you never get this … because the basic idea is, of course, that you are going to work on the same model, as long as you do not have the same IT platform, you would never do that." (CEO, Timber frame builder)

The overall key functionality of the BIM system in this project can be described as a system of "automation islands." By the term "automation island," we refer to the fact that the actors use their systems only rarely to communicate with each other. Designers used BIM technology as a mere enhancement tool for their individual design processes and exchanged full-fledged models only on rare occasions. The main information exchange between these "islands" was facilitated by traditional communication tools such as snapshots of the models and presentations at regular design meetings. According to the actors interviewed, the key functionality of the BIM system could have been significantly enhanced by the establishment of a shared BIM server or platform to facilitate the information exchange.

4.4. Structure

We define the structure of a shared information system, such as BIM, as "the scope and volume of structural relationships among participating organizations" (Lyytinen and Damsgaard, 2011, p. 498). The structure may vary from simple didactic relationships to complex industry wide hubs. We argue that the structure of the BIM system in the case project can be best described as a hub and spoke configuration. A criterion for labeling an IOIS as a hub and spoke configuration is that the system spans a single industry and involves at least three adopters (ibid.). The case project's configuration consists of six BIM adopters and all of them work in the architectural, engineering, and construction industry.

A second criterion for labeling the structure of an IOIS as a hub and spoke constellation is the presence of a central "hub" or "middleman" coordinating the activity and information flow within the IOIS. In the case project, the organizational roles regarding the BIM were not clearly assigned. However, we argue that the architectural firm acted, at least to some degree, as a central "hub" in the BIM system, since they communicated with all the other actors via the BIM system (except for those who had not adopted the technology). Ergo, "one-to-many" BIM communication with the architect as a central actor took place in the case project. Moreover, the architect's firm received all of the firm's designs in paper form, virtual models, or drawing sets. A visualization of the "hub" and "spoke" constellation within the case construction project can be found in Figure 1.

When interviewing the structural engineer (timber structure), we found that their entire information flow was facilitated by the timber frame builder. The structural engineer (timber structure) stated that their role in this project was somewhat special, as they were used to taking a more central role in project communication. They argued that their decision of mainly relying on the timber frame contractor to manage the project communication was firmly rooted in language difficulty issues. They were used to communicating in German, whereas the other parties were communicating in Norwegian. The timber frame builder, however, had positioned a bilingual designer, speaking both Norwegian and German, at project level. However, a second reason for entrusting the timber frame contractor with their project communication was put forward by the structural engineer. They argued that a participation in bi-weekly project meetings in Norway would have been too costly due to their firms' geographical location in Switzerland. No digital means such as video conferences were deployed to facilitate the project meetings.

Three organizational actors—namely, the client, the fire-protection engineer, and the geotechnical engineer (depicted by the white square in Figure 1)—did not actively participate in the case project IOIS, as they did not have BIM modeling systems in place. The geotechnical engineer stated that they did not deploy systems that were able to integrate GIS data into BIM models. The fire-protection engineer stated that s/he designed the fire-protection details by hand; however, they had acquired a BIM software license to explore the system's usefulness for fire-simulations in future projects. The client stated that they did not deploy BIM systems in their work.

4.5. Mode of interaction

The mode of interaction defines the nature of the business relationships among the organizations, as defined by the IOIS. In the previous section, we argued that the case project's BIM system resembles a "hub and spoke" configuration. In addition, we stated that the architect acted as a "middleman," facilitating the BIM information exchange in the case project. This is our point of departure for discussing the relationships among the actors in the case project.

Typically, the role of a central "middleman" in an IOIS is enforced by both technological capabilities and formal power. Within the case project, however, the architectural firm had the technological capabilities to take ownership and establish routines and guidelines for integrating the business processes surrounding BIM, but no formal power to do so. The lack of formal power can be explained by the absence of contractual agreements specifying the power dependencies among the actors participating in the BIM system.

Moreover, organizing a shared information system is time consuming and costly, and the architectural firm had no financial incentives to commit resources to organizing the shared BIM system, again, due to the absence of a binding contract. This holds equally true for the other parties in the project; none of these had any financial motivation for engaging in a collaborative, BIM-enabled design. This finding may explain the observation that neither the architect, nor any other party attempted to align their systems by creating a shared organizing vision, or by motivating other actors to work in a certain way.

Even though the case project's BIM system was far from being fully functional, it is evident that it was used for design, and that it facilitated some of the project communication. After having ruled out financial incentives and contractual obligations as motives for the use of BIM as a shared system, a possible explanation for its actual use is that the parties used the system voluntarily. A reason might be, for instance, that the actors regarded BIM technology as important in effectively executing their individual design tasks.

When studying the prior historical relationship among the actors, we found that most had a long history of working together. In this respect, many actors knew each other personally from previous projects, which created a working atmosphere best described as a "partnership amongst equals." When asked, most of the actors were satisfied with the project communication levels. Moreover, some stated that the informal nature of interaction and the absence of strict formal arrangements and hierarchies in using BIM benefited the overall collaboration in the project.

Actors can be forced into IOIS interaction through powerful companies trying to reap benefits from using a shared system. In a BIM project, a powerful actor such as a large client's organization could, for instance, require a virtual model for its purposes. A forced mode of interaction is defined by Lyytinen and Damsgaard (2011) as a "conflict" mode. The client's organization in the case project, however, was more or less indifferent toward which design technologies would be deployed by the designers to create the buildings' design. Moreover, when asked if it was of any importance in terms of which digital design tools designers deployed to create the buildings' design, the client's CEO responded that only the buildings' appearance and their physical qualities were of importance, and the way in which this was achieved was of less importance:

> "No, but it [the building] has to look new and modern and so on." (CEO, Client)

Thus, we argue that the interaction in the case project's BIM system happened informally and voluntarily, and no obligatory and hierarchical relationships between the actors could be identified. Lyytinen and Damsgaard (2011) refer to a voluntary mode of interaction as a "matching" mode. A matching mode can be best described as an "electronic partnership for virtual business integration" (ibid., p. 501), with no single actor seeking a dominant position in the system. Thus, we argue that the mode of interaction in the case project's BIM system can best be described as the matching mode.

4.6. Mode of appropriation

Organizational actors attribute different significances to BIM technology. These attributed significances or appropriations of technology shape the actors' participation in a shared system. A way to identify organizational appropriations of BIM technology is to identify what kind of attention is paid to IT, in general, or BIM, in particular, in their organizational strategies. Several of the actors interviewed stated that their firms were actively involved in screening the market for technological innovations that would be useful in terms of improving their work. The following statement by the architect highlights the actors' interest in using modern technology:

> "… of course, so we are looking out for new technologies and applications to help us do what we are doing every day." (Architect)

To understand the actors' attitude toward innovative technology, including BIM, we asked them how they would evaluate the innovativeness of their firms when compared to others in the industry. Most actors considered their firms to be innovative and to be among the leading-edge firms within their respective disciplines in the Norwegian marketplace (i.e. structural, electrical and HAVAC engineers, timber frame builders, and geotechnical engineer):

> "There are many good people in good firms out there and I believe that we are up there in the top, for instance, this is the first project we are running on MagiCAD and MEP for electrical systems, and I don't believe that there are many companies in Norway that use this software at the moment." (Engineering design coordinator)

> "I do not think that you will find today another [timber frame] company in Norway that is able to build a project like this." (Drafter, Timber frame builder)

> "The company is very competent in our discipline, where a lot of experience and personal skills make us among the best. This statement is also based on feedback from clients based upon questioning them as to how satisfied they are with our work. This company was, if not the first, one of the first consultant companies to implement BIM for building design." (Geotechnical engineer)

In addition, we asked the interviewees whether their organizations had formulated strategic goals toward using BIM technology in their operations. In addition, we found that, for instance, some of the firms had established practical guidelines for working in BIM and had set the goal of participating in as many BIM projects as possible:

> "Yes, absolutely, we have a very clear strategy toward BIM projects. We want to get involved in as much of the BIM projects as possible. Big, big, BIM projects." (Engineering design coordinator)

> "… this company is based on technology; it's based on the 3D model, that is the whole idea." (CEO, Timber frame builder)

However, to understand the significance attributed to BIM technology at the project level, we considered it valuable to ask the individual designers drawing hands on with BIM tools to what extent they considered BIM technology as important for doing and sharing their work. Most of the interviewees replied that they saw improvements when using this technology related to the clarity, accuracy, and visualization of the design information shared:

> "We understand better when we see things in 3D." (Geotechnical engineer)

> "It makes it much easier to understand where you are; you can see the heights and "ah, ok it's like this" instead of just having a 2D drawing. But, then again, it's more difficult to draw in a model. You have to be more precise, you can't do any cheating. No easy solution." (Engineering design coordinator)

> "It is a big difference, of course, that we are kind of building a model with parametric objects—it's not only lines, it's a window model, and you are taking this information out of the model afterwards, and we get, in a way, schemata for windows and doors and so on, and all these things, so that is maybe the biggest difference. It's sort of simplifying the process of making the documents for the building." (Architect)

> "I have lots of both good and bad experiences and frustrations, and I also see some hopes for the future." (Design manager, Timber frame builder)

Maybe the clearest indicator for the organizational appropriation of BIM systems is to observe their behavior at project level. For instance, most project actors created virtual models, even though they would have fulfilled their contractual obligations by delivering 2D drawing sets created in traditional 2D CAD software. According to the engineering design coordinator, it would just have taken a little more precision and a little more effort to run this project as a full-fledged BIM project. Moreover, most of the drafters had been trained by their employers in designing with BIM software and were experienced users. Thus, we argue that most actors in the case project attributed a high significance to BIM technology.

However, there were some exceptions as the fire-protection engineer, the geotechnical engineer, and the clients' organization did not deploy BIM technology at all. Moreover, the HAVAC designers decided deliberately to design in 2D, even though they had the competence and software in place to create 3D virtual models. The client's appropriation of BIM technology was low when compared to the other actors. When asked if they would be willing to pay extra for receiving a virtual model once the design was completed, the client's CEO stated that they did not need a model:

> "Nope, we do not need it [a virtual model]." (CEO, Client)

5. DISCUSSION

Our findings make it possible to understand why the case project's BIM system functioned in the way in which it did. An overview of the key findings of our analysis can be found in Table 3. We found that many actors had substituted their old 2D CAD systems with the new BIM technology. In addition, the BIM software applications deployed at project level were technically interoperable and the actors attributed a high significance to the new technology. Thus, we argue that several preconditions for a fully functional BIM system have been met in the case project. However, the inter-organizational processes in our case project still resembled, in essence, traditional, 2D working routines. This finding is in line with earlier research arguing that many processes surrounding 2D CAD are institutionalized and taken for granted in construction projects (Baxter and Berente, 2010). Moreover, it is widely accepted that it is not easy for actors to separate their work practices from the underlying logic of 2D design (ibid.).

Our findings led us to conclude that replacing old technology with new, and concurrently leaving old processes intact leads to the emergence of "automation islands." By the term "automation island," we refer to the fact that actors use the new technology predominantly to automate old design processes rather than to substantially transform the way in which they communicate their designs. This reflects an untapped potential similar to that which was pointed out in early reengineering literature (Hammer, 1990). Our findings thus support the argument made in contemporary literature that BIM's "transformational capability" to change the way construction organizations do business is frequently left untapped (Ahmad and Sein, 2008; Ahmad et al, 2010).

TABLE 3: BIM adopter configuration in the case project

Adopter configuration element	Case project's adopter configuration
Organizing vision	• Neither formal nor informal arrangements toward BIM have been established • No attempts to create a shared organizing vision could be identified • Actors simply did not know with what software the others worked • Actors used standard design-bid-build contracts • No evidence for the existence of a shared organizing vision of BIM
Key functionality	• Full-fledged BIM models were only exchanged on rare occasions • Actors mail back and forth snapshots of their models • Main information exchange via meetings and other traditional means • The BIM applications in use are technically interoperable • Three actors did not deploy BIM-ready design tools • No shared BIM server or IT platform • Overall 'dysfunctional' BIM system • System of 'automation islands'
Structure	• One-to-many BIM communication evident • 'Hub and spoke' constellation with the architect as central hub • Three actors could not participate in the system
Mode of interaction	• Hub role enforced by architect's technical capability • Hub role not enforced by formal power • Hub had no financial incentives to coordinate design • Spokes had no financial incentives to work in a shared BIM system • Interaction can be described as a "partnership among equals" • Client as powerful actor was indifferent about BIM use • Actors' use of BIM voluntary to improve individual design processes • 'Matching' mode of interaction
Mode of appropriation	• Most actors attributed a high significance to BIM technology • Client did not attribute a high significance to BIM technology • Actors had personnel trained to design in BIM • Actors had up to date BIM applications in place • Actors' organizational strategies enforce the use of BIM systems • Most actors perceived themselves as leading-edge innovative firms in Norway

Literature reports that transforming design practices requires significant departures from established practices beyond simply substituting technology (Baxter and Berente, 2010). Moreover, it is well-established knowledge that a fully functional BIM system can only be achieved by changing a set of contractual and organizational arrangements toward working together in BIM (Whyte and Lobo, 2010). We add to this literature by suggesting that, based on our findings, a "shared organizing vision" toward BIM is an essential precondition to changing old design practices.

Despite having well-trained people, up to date software, and interoperable systems, the actors in our project made no attempt to create such a vision. Our findings allowed us to understand that actors need a clear understanding of what can be gained by operating a fully functional BIM system before they will engage in changing inter-organizational processes.

Practitioners in our case project had conflicting views about the business value of operating a fully functional BIM system and aligning their processes. First, the architect opposed strict working routines toward BIM, arguing that this would hinder free and dynamic design expression. Second, the engineering design coordinator opposed the alignment of processes. They argued that running a fully functional BIM system would require more design precision and additional work, which would be costly. Third, the client was indifferent toward the functionality of the BIM system. Fourth, the timber frame builder was in support of a fully functional BIM system. This actor’s work required a high level of design precision and detail. Last, there were actors who expressed an interest in participating in the BIM system without having the technical capabilities of doing so (geotechnical engineer, fire-protection engineer). We claim that the presence of many different, and at times, conflicting organizational interests in BIM’s functionality led to actors retaining their old processes at inter-organizational level.

Further, we found that project actors did not actively question their traditional communication routines and that they communicated little about the way in which BIM should be used to facilitate their inter-organizational communication. Thus, we argue that this absence of meta-communication about BIM could be an alternative explanation for the emergence of the automation islands. For the purpose of our paper, we define meta-communication as “all exchanged cues and propositions about (a) codification and (b) the relationship between the communicators” (Ruesch and Bateson, 1951, p. 209). Given the earlier mentioned conflicting organizational interests toward a fully functional BIM system, we find it surprising that inter-organizational routines were not up for discussion. We argue that a fully functional BIM system only comes within reach if actors actively discuss and agree on the modalities of BIM communication.

However, our work has limitations, rooted in the key characteristics of the project under study. First, we developed our view on configuration analysis based on a single case study and interviews with a selected sample of the project participants. Even though we argue that our findings have relevance beyond the case project studied, additional research studying multiple projects and contexts is needed to further validate this. Second, some of our findings may be attributed to the type of construction project studied; namely, a residential project. The client in our case project developed residential apartment units to sell them shortly after completion. We argue that the client had little interest in a fully functional BIM model, since they were not concerned with the operation of the completed building. Arguably, clients involved in projects in which they have to operate the building throughout its life cycle (e.g. commercial, industrial, or infrastructure projects) might have a stronger interest in a fully functional BIM system. However, this claim needs to be validated by further research. Second, some of our findings may be attributed to the degree of complexity of the construction project. The three buildings constructed were similar in design and size (e.g. design repetition). It made the design and construction less complex. Therefore, arguably, a fully functional BIM system might be less relevant in this context. However, the relationship between BIM and a building’s complexity needs to be examined. This is an interesting future research avenue. Thus, further research should analyze multiple projects differing in type and complexity by using the configuration analysis lens to identify the major weaknesses in today’s BIM practice and how they can be resolved. In addition, our analysis pointed to the need for further research on the business value of BIM beyond the study of first-order effects such as BIM’s impact on scheduling or cost accuracy. Moreover, further research should seek to explain how multiple actors could overcome conflicting organizational interests to transform the process of construction design.

6. CONCLUSIONS

We have shown the usefulness of configuration analysis as a theoretical model to analyze, explain, and understand the BIM-enabled interaction in a construction project. Throughout our analysis, it became apparent that the structured analysis of the key elements constituting an adopter configuration could lead to a holistic understanding of actors’ behavior in a shared IOIS. Our work has established that it is not a given that a set of well-trained, BIM-ready organizational actors makes use of BIM to jointly develop design solutions. Moreover, we found that the actors have diverse opinions about the benefits of a fully functional BIM system. Thus, our article complements and reinforces existing research on BIM adoption by providing an insight into the communication practices and the areas in need of managerial attention when BIM is used for integration in digital construction design projects.

Our findings illustrate several weaknesses in existing practice in terms of integrating BIM business processes. While most actors had substituted their old design technology with BIM, we found that they still created their virtual models largely in isolation, instead of collaborating effectively. The organizations thus substituted old technology for new BIM technology without transforming inter-organizational structures and processes. We therefore argue that leaving old, cross-organizational processes intact leads to the emergence of “automation islands.”

In terms of practical contribution, we argue that our study complements the current development on BIM adoption. Scholarship on BIM adoption has, to date, been largely focused on the technical requirements of BIM, and on the definition of new standards for information exchange, but less on the inter-organizational practices surrounding the modeling activity (Dossick and Neff, 2011). By conducting a configuration analysis, we were able to point out both leadership decisions and communication practices that were required to enable a fully functional BIM system: the creation of an organizing vision, overcoming conflicting motivations, and the active discussion of BIM modalities. We identified several aspects where improvements might be possible. Improvement is possible by creating a shared organizing vision toward working together in BIM. In this respect, actors need to discuss desired communication outputs and the role of ICT in facilitating such communication. Furthermore, actors need to mitigate for discontinuities caused by different languages, firm location, and technical capabilities. They could, for instance, use shared information systems such as videoconferencing tools and online repositories to exchange drawings, models, documents, and information surrounding the BIM model. Moreover, a “critical mass” of actors needs to be convinced about BIM’s business value at inter-organizational level to make it work. In our case project, with only one actor (the timber frame builder) expressing an organizational interest in a fully functional BIM system, this “critical mass” was not reached. In this respect, project actors need to identify and discuss what might be gained by operating a shared system. Especially those actors who are interested in a functional BIM system, should actively seek discussion, and build coalitions with others having similar interests. Naturally, the aforementioned improvements are only within reach for BIM adopters. However, we did identify that some designers in today’s practice continued to struggle in terms of overcoming the technical hurdles to BIM adoption. Especially, issues related to the integration of BIM and GIS, and other advanced engineering systems remain unsolved.

We developed our view on configuration analyses by exploring a single construction project. While we argue that the chosen case is typical for projects in the AEC industry with regard to the actors involved and the actors’ digital modeling practices, our findings need to be validated beyond the project studied. Thus, we recommend further research analyzing multiple project types and complexities using the configuration analysis lens. Further, we recommend research exploring how conflicting organizational interests in a fully functional BIM system can be overcome.

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Article 3

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How Is Building Information Modeling Influenced by Project Complexity? A Cross-case Analysis of e-Collaboration Performance in Building Construction

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ABSTRACT

Virtual design and construction of buildings and architectural spaces require extensive collaboration among a diverse set of design professionals. We analyze e-collaboration performance in two construction projects of differing complexity, to gain an understanding of how collaborative design based on building information modeling (BIM) is influenced by the complexity of the building project. The findings suggest that the perceived business value of BIM depends on project complexity and that BIM-based collaboration does not yield unconditional positive implications for all types of construction projects. We argue that current practice would benefit from a more structured approach to building business cases for e-collaboration, comprising the following aspects: 1) a thorough assessment of BIM's potential benefits based on the complexity of the project; 2) an assessment of all designers' collaborative BIM capabilities and maturity; 3) a reliable cost estimate for full-scale BIM e-collaboration; and 4) a cost benefit analysis to identify the business value of BIM-based e-collaboration. In addition, a systematic approach to collaboration engineering would be required to develop e-collaboration environments customized for the information needs of a specific project.

Keywords: Building Information Modeling, project complexity, e-collaboration, design practice, building construction

INTRODUCTION

Designing buildings and architectural spaces requires extensive collaboration among a diverse set of design professionals. Experts from various disciplines, such as architects, structural engineers, and landscape designers, develop design solutions in collaboration (Gal, Lyytinen, & Yoo, 2008). Using next-generation virtual design technologies such as building information modeling (BIM), the construction industry has data-sharing technology powerful enough for integrated and concurrent digital design of facilities. BIM technologies can best be described as a platform of IT tools used in designing virtual models that present all functional and physical characteristics of a building (National Institute of Building Science [NIBS], 2007). BIM is regarded by many as a core technology for aiding collaboration among the actors in the Architecture, Engineering and Construction (AEC) industry.

BIM-based collaboration may be necessary and desirable, but research indicates that this is not easy to achieve (Isikdag & Underwood, 2010; Shen et al., 2010). This is partly due to BIM applications not living up to the industry vision of their use as inter-organizational collaborative tools (Neff, Fiore-Silfvast, & Dossick, 2010), and issues related to the new ways of organizing required to create interoperable processes for information exchange and storage (Ahmad & Sein, 2008). Additionally, AEC firms exist along a spectrum from "highly computer literate firms to those that hardly use computers in their work," which leads to dissimilar expertise and knowledge in using advanced information systems (Williams, 2007). Many AEC organizations remain skeptical about changing established work practices in response to new information systems (Guha, Thakur, Konar, & Chakrabarty, 2011).

Even in leading BIM projects run by leading construction firms, seamlessly integrated practice remains elusive: "Findings from the evaluations indicated that the winning submittals continued historical success in the area of visualization, whereas opportunities for virtual analysis and other critical areas still remain relatively unexplored, even in the 'best BIMs in the world'" (McCuen, Suermann, & Krogulecki, 2012, p. 224). On the upside, several scholars report performance gains in projects where organizations succeed in using BIM technology collaboratively (Manning & Messner, 2008; Khanzode, Fischer, & Reed, 2008). Reported gains include decreasing the number of change orders, reductions in unnecessary rework, and decreased need for clarification (McGraw-Hill Construction, 2012). A recent study argued for the need to inquire further into whether collaborative BIM use is contingent upon individual project characteristics such as project size, value, and complexity (Bryde, Broquetas, & Volm, in press). In addition to the specific project characteristics, collaborative BIM performance depends upon organizational ICT maturities and capabilities (Succar, Sher, & Williams, 2012).

Following up on the call by Bryde et al. (in press) and a recent literature review suggesting further research on BIM based interorganizational collaboration practice (Merschbrock & Munkvold, 2012), we investigate how and whether collaborative BIM performance is influenced by the complexity of a construction project. Project complexity has been defined as "consisting of many varied interrelated parts" and can be operationalized in terms of differentiation and interdependency (Baccarini, 1996, p. 202). Differentiation refers to the "number of varied elements, e.g. tasks, specialists, components," and interdependency refers to the "interrelatedness of these components" in a project (Baccarini, 1996, p. 201).

We contribute to the ongoing discussion by studying the intertwined nature of project complexity and collaborative performance in digital construction design, and by suggesting how current practice can be improved. Thus, our research is guided by the following question: How does project complexity influence BIM-based collaborative performance in construction projects?

To address this question, we present the results of a comparative case study of two Norwegian construction projects that analyzed digital modeling performance based on an assessment metrics provided by Succar et al. (2012). The construction projects differ in their design complexity, taking into account if and how project participants respond to varying complexity in their collaborative efforts. The intended contribution of this article is twofold; we seek to identify how project complexity influences BIM-based collaboration in these two cases and to provide practical suggestions for addressing related challenges.

The paper is organized as follows. The second section introduces the theoretical perspective supporting our analysis. The third section documents the research methodology, and the fourth and fifth sections present the analysis of the two case projects followed by a discussion of the results. The sixth section presents the conclusions and implications of our work.

THEORETICAL LENS

We base our study on research on collaborative performance, to be able to compare the extent to which the actors in our case projects use BIM to facilitate their collaborative work. Collaborative performance has been defined as a "compound metric of collaborative effectiveness and collaborative efficiency" (Kristensen & Kijl, 2010, p. 60). Efficiency here refers to the resources consumed and gained by collaborating, and effectiveness is the degree to which collaborative work aids goal achievement. Collaborative performance in BIM-based design depends on, among others, actors' past experiences in collaboration, the uptake of BIM, and existing ICT infrastructures. The collaborative capability of individual actors thus influences the overall collaborative performance in modeling. Collaborative capabilities has received attention from researchers studying individual, team, and intra- and interorganizational relationships (Blomquist & Levy, 2006). Collaborative capability has been defined by Blomqvist and Levy (2006) as "the actor's capability to build and manage network relationships based on mutual trust, communication and commitment" (p. 31). Tyler (2001) offers a somewhat more detailed definition of collaborative capabilities as "consisting of information processing, communication, knowledge transfer and control, the management of intra- and inter-unit coordination, trustworthiness or the ability to engender trust, and negotiation skills" (p. 2).

Teamwork is challenging when BIM capabilities differ, and sophisticated users of BIM work with non-BIM users on projects (Porwal & Hewage, 2013). Recognizing the importance of strong and evenly distributed BIM capabilities at the project level, collaborative capabilities has received attention in current BIM research (Succar et al., 2012). At the same time, AEC practitioners and especially large construction clients, realizing the importance of BIM capabilities, have begun to select project team members based on prior BIM experience (McGraw-Hill Construction, 2012). AEC researchers are studying the level of organizational BIM uptake and whether or not this uptake is moving toward integrated practice (Haron, Marshall-Ponting, & Aouad, 2010).

In addition, the structured assessment of collaborative capabilities has become a highly focused topic in ongoing BIM research. Several frameworks useful for measuring collaborative BIM performance can be found within this stream of research. These frameworks are useful for several reasons: 1) The frameworks provide a conceptualization of collaborative capabilities, 2) aid in understanding of collaboration issues, 3) can guide the selection of BIM solutions, and 4) provide an understanding of baseline collaborative capabilities in the project (Munkvold, Weiseth, & Larsen, 2009). Moreover, maturity assessment is important for practitioners to achieve mutual agreement on organizing inter-organizational structures and processes in e-collaboration (Merschbrock, 2012; Subrahmanian et al., 2003). An example of a BIM-specific framework is the Interactive BIM Capability Maturity Model (I-CMM) proposed by the U.S. National Institute of Building Sciences (NIBS). This model is in its essence a further development of the Software Capability Maturity Model (CMM©) developed by the Software Engineering Institute (SEI), customized for BIM technology. The I-CMM model has been applied to study practice in contemporary construction projects (McCuen et al., 2012), and some researchers find the model useful for understanding BIM performance in projects and pinpointing areas that need improvement (McCuen, 2008). However, the I-CMM model has been criticized for its limited applicability to practice, rooted in its complexity and variability in score ratings (Succar, 2009).

An alternative to this model is the Building Information Modeling Maturity Index proposed by Succar et al. (2012). This BIM performance assessment model is based on five complementary components that can be used in any combination: (1) capability stages, (2) maturity levels, (3) competency sets, (4) organizational scales, and (5) granularity levels. The first components of the model are BIM capability stages, which represent milestones describing the degree and intensity of BIM-based collaborative activity. A definition of each BIM capability stage is presented in Table 1.

Table 1. Capability stages in collaborative BIM design (Succar et al., 2012)

Pre-BIM status	Organization creates 2D documentation to describe the building and occasionally 3D visualization created in non-object-based design systems. Collaborative design is not prioritized. Design flow can be characterized as linear and asynchronous. Low investment in technology and interoperability. Examples of drawing practices used at this stage are 2D drawings drawn by hand, 2D CAD drawings, and non-object-based 3D visualizations.
BIM Stage 1	Organization uses BIM parametric object software. Software is deployed within the organization to create single disciplinary models. Software is used to automate 2D drawing and for simple data export operations such as extracting door schedules, concrete volumes, and so forth. Collaborative practices are similar to pre-BIM status.
BIM Stage 2	Organizations have developed expertise in generating disciplinary models. In stage 2, organizations collaborate by exchanging digital models either by interchanging proprietary formats or based on full-fledged models.
BIM Stage 3	Organizations create jointly semantically rich BIM models based on model server architecture. Models can be used for complex analysis and simulations. Collaborative work now spirals iteratively around a sharable model.
Integrated project delivery	All pertinent BIM visions are included in one model regardless of their originating sources. A highly integrated multi-dimensional model connected to external databases is the outcome of this stage. Building management systems, geographic information systems, cost databases, and other systems are linked and included in the model.

The second measure refers to the “quality, repeatability and degree of excellence” designers achieve when collaborating at different BIM capability stages (Succar et al., 2012, p. 124). The BIM maturity levels suggested by Succar et al. (2012) range from (1) ad-hoc, (2) defined, (3) managed, and (4) integrated to (5) optimized collaboration maturity. In the context of our study, we use the *ad-hoc* maturity label to describe situations in which collaboration is conducted, but in an ad-hoc and improvised manner, not following any particular logic (Magdaleno, de Araujo, & Werner, 2011). *Defined* maturity describes situations in which designers plan their communication, and there is a social awareness of this agreement. The label *managed* is used to describe situations in which communication is planned, with information distributed and tracked by a centralized management function. At the *integrated* level, collaboration is a self-sustained effort where individual actors are aware of the manner in which the group collaborates and share knowledge and information freely. At the *optimized* level, processes are systematically managed by a combination of continuous improvement and process optimization.

The third component of the Building Information Modeling Maturity Index addresses the organizational BIM competency sets useful for assessing technological, process, and political abilities required for operating a shared BIM system. The organizational scale component has been developed to match the depth of the BIM assessment to the organizational context in which the assessment is supposed to take place. Finally, granularity levels is a measure developed to provide the assessors the opportunity to customize the assessment regarding the breadth of the assessment, its scoring detail, and the expertise of the assessor.

We applied the capability and maturity components of the Building Information Modeling Maturity Index to assess the degree and intensity of collaborative work and the maturity with which actors conducted this work. We did not include the other components of the model, as these were developed for "highly detailed, formal and informal organizational audits" (Succar et al., 2012, p. 136), which is beyond the scope of our work. We seek to understand the influence of a project's complexity on collaborative performance, rather than to conduct organizational audits. Combining these two assessment measures allows for understanding the BIM-based collaborative performance of our case study projects.

METHOD

The wood-based building industry in Norway has invested heavily in automation and technologies such as BIM. Recent legislation in Norway, such as the new standards for developing low-energy and passive houses, and clients pressuring for reasonable quality, have created a need for new technologies and innovation. This part of the AEC industry, striving for better integrated practice, makes a compelling context for studying the interplay of collaborative performance and project complexity. We present the results of two case studies conducted in Norwegian wood-based construction projects. The case study approach is appropriate for understanding collaborative design in construction projects, as a case study investigates "sticky, practice based problems where the experiences of the actors are important and the context of the action is crucial" (Benbasat, Goldstein, & Mead, 1987, p. 370).

The case projects were selected based on four criteria: 1) the project participants should resemble a typical project team in the industry (e.g., client, architect, engineers, and contractors); 2) the design stage had to be completed when the data were collected; 3) BIM technology had to be used in the construction design; and 4) the project complexity for the two cases should be different. These criteria provide a holistic account of construction design activity, to understand the perspectives of all actors typically involved in this activity, to place BIM as a technological artifact at the core of our study, and to understand how project characteristics influence collaborative design.

We conducted one case study in an architecturally complex and challenging project, which was an ambitiously designed library (Case A), and one in a less complex construction project, a residential building project (Case B). The library's design was highly *differentiated* as it consisted of numerous varied elements whereas the residential project consisted of standardized repeated elements. In addition, the library's designers were considerably *interrelated* in their work tasks as designing numerous varied elements requires a high level of coordination. High degrees of differentiation and interrelation are indicators of complexity, and thus, the library's design was more complex than the design of the residential buildings (Baccarini, 1996). This gave us the opportunity to develop an understanding of whether and how the complexity of a construction project influences the degree of BIM use in design. More details of the case project characteristics are in Table 2.

Table 2. Project characteristics of the two case studies

	Case (A) Library	Case (B) Residential project
Architectural features	Library, café, meeting places, and administrative areas	One hundred apartment units
Design complexity	Ambitious design of gradually shifting shapes resembling hybrid structures, numerous varied elements, high level of *differentiation*, high *interrelation* between design tasks	More or less "industry-standard" design, limited number of varied elements, low level of *differentiation*, lower level of *interrelation* between design tasks
Type of production	One-of-a-kind production, project form of organizing, labor intensive, low automation, prefabrication of wooden components, and a large degree of on-site assembly	Serial production of architectural modules, with repeated wall shapes; standardized interfaces between modules; guided by a set of defined design parameters to allow for serial/factory production defined by the load capacities of trucks, cranes, and on- and off-site plant and equipment, project form of organizing, less labor intensive, high automation, prefabricated modular building elements
Type of building	wooden structure	wooden structure
Profession of the 19 persons interviewed	Engineering Design Manager, Structural Engineer, Electrical Engineer, Fire-protection Engineer, Massive Wood Builder (Project Manager), Glue-lime Builder (Project Manager), Client Representative (Municipality), Architect, General Contractor	Timber Frame Builders (CEO), Design Manager, Production Manager (Drafter), Engineering Design Coordinator (for HVAC, structural, electrical), Geotechnical Engineer, Fire-protection Engineer, Client Representative (CEO), Structural Engineer for Wooden Structures, Architect

From September 2011 to May 2012, we conducted semi-structured interviews with 19 professionals involved in design and construction in the two projects. Eight of the interviews were conducted via Skype due to the firms' locations in geographically distant regions of Norway and in foreign countries (e.g., Switzerland), while the remaining interviews were conducted face-to-face at the companies. Each interview lasted about 1 hour. The interview strategy chosen allowed us to capture in depth the ongoing design interaction in the case projects. An overview of the persons interviewed and their profession is presented in Table 2. Moreover, the first author's civil engineering background comprising work experience and university-level education helped to minimize the potential dissonance between the interviewer and the respondents. All interviewees were informed beforehand about the modalities of the interviews and gave informed consent. The interviews were recorded and, transcribed, and coded by uploading transcripts as documents into NVivo9. Nodes were assigned to ideas that could be related to the actors' collaborative capabilities and their maturity in accomplishing BIM-based design work. In addition, we identified ideas related to the complexity of the projects.

FIRST CASE STUDY: THE LIBRARY

The setting of the first case study is the design and construction of a library and cultural center in southern Norway. The project comprises the construction of a library, including a café, meeting places, and administrative areas. The building's gross floor area is 1,938 m^2. The building's wooden structure consists of 27 ribs made of prefabricated glue-laminated timber elements and computer numerical control (CNC) cut plywood boards. The library design is ambitious, with the ribs gradually shifting shapes resembling hybrid structures. The building design has received national and international attention and has been awarded several architectural design prizes.

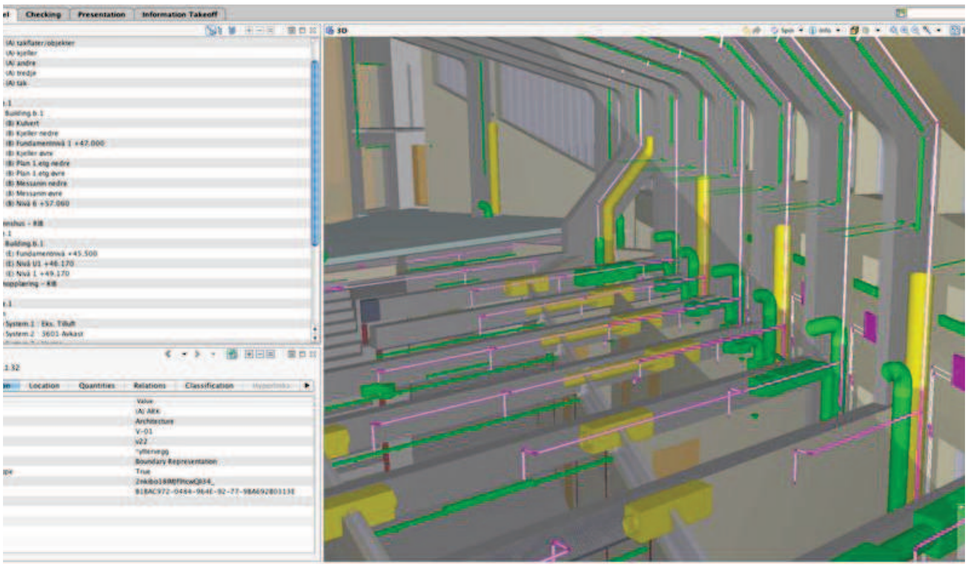

Figure 1. BIM visualization of the library's installations (©2013 Helen & Hard, used with permission)

Figure 1 provides an inside view of the library to give an impression of its design. The view is from snapshots taken of the project's BIM model in model viewing software, and shows the technical installations embedded in the building's wooden structure.

Collaborative Capability

The designers each created their individual contribution to the library's design; the architect created a model signifying the outer shape and appearance of the building, the structural engineer created a model presenting the structural elements (load-bearing walls, slabs, columns, beams, etc.) relevant for the stability of the building, and the Mechanical, Electrical and Plumbing (MEP) engineers modeled technical installations such as ducts, pipes, and cable carriers. In this section, we assess each actor's capability to engage in collaborative work with others while generating their individual designs. We use Succar et al.'s (2012) framework to rank the collaborative capability of each designer.

The architect created three "types" of virtual models: 1) photorealistic rendered surface models, 2) 3D sketches, and 3) architectural BIM models. Further, the architect used object- and non-object-based design technology to create the different types of visualizations. For instance, to produce the rendered surface models, he deployed non-object-based rendering software operating on Non-Uniform Rational Basis Spline (NURBS) technology. The application, called Form-Z©, was used to create a photo-realistic 3D-surface model signifying the materiality, illumination, and shading effects of various types of materials used in the building's façade. In addition, the architect used a simple 3D drawing tool called SketchUp® to quickly communicate project details based on digital sketches. Similar to the rendering software, the sketching software was non-object based and thus not particularly suited for situations in which e-collaboration is prioritized. The sketching software was simply used to display a specific detail to others to trigger a discussion about it.

The third system used in the architectural design was the object-based BIM application ArchiCAD™. This system was used to create disciplinary architectural models, to automate 2D drawing production, and to create exchangeable digital model replica. A model replica based on the Industry Foundation Class (IFC) file exchange format was created for exchanging designs with the structural and MEP engineers. Bi-weekly design meetings were held on the engineering firms' premises to facilitate the exchange among the four parties involved (architect, structural, electrical, and HVAC engineers). In preparation for these meetings, each party provided disciplinary IFC models signifying the latest design progress. The IFC models were then combined into a joint building model to verify quality, align the design, and fit the individually created sub-models into the building as a whole system. The designers used Solibri™ software to "assemble" the individual IFC sub-models into a joint building model. Then, this combined model was projected on a screen, and the designers discussed design solutions while conducting a "virtual walkthrough" of the future building.

Through designing based on object-based BIM software in conjunction with exchanging digital models, the architect displayed collaborative capabilities at BIM Stage 2 (ref. Table 1) in the evaluation framework by Succar et al. (2012). The following statement by the architect highlights that assembling individually created sub-models was important to discuss design solutions:

> It [the joint model] was very important in the project meetings, because then we had the 3D model up, and we could manage it by walking around through the building while discussing solutions. […] When we were discussing different solutions, it [the joint model] was extremely helpful […] because then you could actually show on the screen what a beam for example actually means, because this is much easier to do in a 3D model than to do on a physical drawing for example. (Architect)

The engineering design was provided by four specialist designers, namely, a structural, electrical, HVAC, and fire-protection engineer. Naturally, these engineers used various engineering systems to conduct advanced analysis to calculate the size of components such as structural beams, electrical installations, and ventilation ducts, or to conduct simulations for fire growth. In addition to these engineering systems, the designers deployed various information systems to visualize the design solutions. The engineers designed based on object-based and non-object-based applications. The structural engineer, for instance, worked with Autodesk Revit©Structure, an object-based BIM application. The HVAC and electrical designers worked with ProgmanOY©MagiCAD, object-based software suited for electrical and HVAC design. As mentioned earlier, the three designers actively participated in model-based collaboration based on IFC files. Thus, the designers' collaborative capabilities are ranked at BIM Stage 2. The only "outlier" in terms of not using an object-based design system and not participating in digital collaboration was the fire-protection engineer. He created his design based on 2D Computer Aided Design (CAD) software, and is accordingly placed at the Pre-BIM level of collaborative capabilities. In the following quote, the structural engineer explains why he thought model-based collaboration was necessary:

> I think it [the joint model] was important for the first phase. It was a very special timber frame in which the technical installations needed to be fitted. And it [the wooden ribs] was an important part of the architect's design so we had a lot of things happening on very small areas. Therefore, I think BIM was important. (Structural engineer)

The main contractor had neither prior experience in using modeling technology nor any installed software packages useful for creating, viewing, or sharing models. The contractors still used 2D

CAD as their main design technology, and were skeptical about using BIM technology at the project level. We thus ranked the collaborative capability of the main contractor at Pre-BIM. The engineering design manager described the inability of the contractor to participate in model-based collaboration:

> Of course, all the entrepreneurs [needed] some more education, but I did not think they had the time or money in the project to jump there [digital collaboration]. (Engineering design manager)

One of the subcontractors, the massive wood builder, applied object-based modeling technology. He deployed a 3D CAD/Computer Aided Manufacturing (CAM) system. He used it to create CNC production files to produce complex wooden elements such as the two-gabled roof in the entrance and outer and interior wall elements for the library. However, he did not deploy this system to collaborate with others, and his collaborative capability was thus assessed as BIM Stage 1. The other subcontractor (the glue lime builder) worked based on 2D CAD, which indicates collaborative capability at the Pre-BIM level. The engineering design manager reflected on the inability of the main contractor to participate in model-based collaboration:

> I think we succeeded in the first half [of the project in BIM-based collaboration] and then not in the second half. […] We had great focus on BIM at first, and we wanted to get it right from the start. The architect also wanted to become better [in using BIM technology], and then [the main contractor] came in, and I think it just became worse after that. (Engineering design manager)

Collaborative Maturity

In this section, we assess the maturity with which the designers executed their collaborative work. We found that only four of the designers actively participated in BIM-based collaborative work (i.e., the architect and the structural, electrical, and HVAC engineers). The other designers who did not participate in collaborative design activity are not included in this analysis (the fire-protection engineer, main contractor, sub-contractors). None of the participating engineering designers had prior experience in digital design collaboration. This limited experience in model-based collaboration led to practical challenges when the joint model was assembled; e.g., they had difficulty finding shared geometric insertion points. Moreover, the engineering design manager stated they needed to start by developing a working routine for model exchange and assembly before the design work could be executed. The following statement by the engineering design manager illustrates the limited experience:

> This was the first BIM project [where we collaborated with others] so I do not think we knew what we were doing. I think it [combining the BIM models] was good for the project's quality. (Engineering design manager)

Beyond the limited experience in BIM-based e-collaboration, all the designers experienced software- and hardware-related problems that limited their capability to exchange modeling data:

> Technically it was challenging to use IFC as a common format because the physical shape of the building was so complex that both Revit and ArchiCAD had some difficulties translating the model into an IFC format. So we used quite some time and support from ArchiCad to sort out problems just to manage and export data from the 3D Model into an IFC file. But when we did that, it was of course a great advantage. We reduced

misunderstandings in the project meetings and in the project process by a great deal. (Architect)

However, despite the hurdles to collaborative work, including limited experience and technical problems, the (four) designers established a routine for model exchange. However, many actors in the project did not participate in digital collaboration, and the established routines were far from well-integrated practice. The maturity level of the e-collaboration could be classified as more or less “managed” (Succar et al., 2012), because the designers had defined a routine for model exchange (walkthroughs) and information was distributed accordingly.

SECOND CASE STUDY: THE RESIDENTIAL PROJECT

The setting for our second case study is a wood frame, low-energy housing development in Norway. The project includes the construction of three apartment buildings featuring 100 upscale apartment units. The buildings’ structure consists of prefabricated and CNC cut timber elements. The architect optimized the buildings’ design for the use of prefabricated wooden elements. Figure 2 provides a perspective view of the buildings’ digital architectural design with their repeated wall shapes.

Figure 2. BIM model of the residential project (©2013 Trebyggeriet, used with permission)

Collaborative Capability

This section provides a brief account of each designer’s collaborative capabilities, with our assessment based on Succar et al.’s (2012) framework. The architectural office designed based on two types of modeling technologies. In this project, they worked with non-object-based 3D sketching software (SketchUp®) and object-based BIM software (Revit©Architecture).

The former technology was used to quickly create and communicate visualizations of project details. These sketches were not used in digital collaboration, other than to visualize and discuss specific design solutions. The non-object-based sketching software can be classified as a Pre-BIM type of technology. The architect describes his motives for using this technology:

> I used SketchUp to take snapshots of my model, and I used, of course, hand drawings and sketches … just in a way to get along, and try to show what we are thinking, and so on. So, it's kind of dynamic, the way we like to do it. It is the fastest way to do it by hand and a quick sketch in a way. For more complex things, I would maybe use a SketchUp model as a background for the sketch I make by hand, and so on. (Architect)

The architectural BIM design software was primarily used as a tool to automate the architect's production of 2D paper drawings. In this project, the architect did not prioritize collaborative BIM-based design and exchanged modeling information only occasionally with some of the engineers. At the project outset, the architect made an architectural model available that was used as an "envelope" for the engineering design, but the designers did not "assemble" their models into a joint BIM model. Moreover, the designers did not use model checking software or a model viewer. Much of the collaboration was facilitated by sending snapshots of models back and forth. Thus, the collaborative capability of the architect can be ranked at BIM Stage 1. The following statement emphasizes our assessment of the architect's collaborative capabilities, as he did not use the modeling resources provided by others:

> We have not used the service model, and I do not know whether the service engineers, ventilation, and so on used 3D modeling . . . I have not used their model to check my things. (Architect)

In contrast to the architects, the engineering office providing the structural and MEP design had extensive prior experience in object-based based design and collaboration. The engineers had software such as Revit©Structural, Revit©MEP, and MagiCad™ in place, allowing them to design based on digital BIM models. Additionally, they had systems such as NAVISworks™ and Solibri™, which would have allowed them to run a managed BIM-based collaboration. And according to their design manager, it would have taken only a little more effort and precision in the design to run a full-fledged BIM-based collaboration at the project level. However, even though they had prior experience in collaborative BIM-based design and capabilities allowing them to work at BIM Stage 2, they decided not to engage in collaborative design. They focused on producing 2D CAD drawings. Thus, we rank their collaborative capabilities in this project as BIM Stage 1. The engineers did not prioritize collaborative BIM design due to the project's "simple" and "ordinary" nature:

> We haven't been doing that [BIM-based design] in this project for the technical installations, it's a quite simple project, it is not necessary to do a lot of collision controls because we don't have what you call a large cable routing. . . . If we just have an ordinary project that is not really complex, and we have a good feeling, then we use MagiCAD because it's much faster to draw with. (Engineering design coordinator)

The geotechnical and the fire-protection engineers relied on their old 2D CAD systems to create designs, and they were therefore not able to participate in collaborative BIM modeling. The geotechnical engineer created a virtual terrain model by using a geographic information system (GIS), and used a 2D drawing system (AutoCad©) to create drawings. However, the CAD system was not designed to create parametric objects. The fire-safety engineers created hand sketches to provide their services. Thus, the collaborative capability of these designers can be classified as the Pre-BIM level.

The timber frame builder automated their production line with an end-to-end CAD/CNC production system. The timber frame builders and the consulting engineer responsible for approving the structural details of the wooden elements had object-based BIM systems in place. They used the systems to create 2D paper-based workshop drawings and machine-readable CNC files. Their collaborative capability can be classified as BIM Stage 1. The following statement by the timber frame builder's CEO provides evidence for our BIM capability assessment:

> This company is based on technology; it's based on the 3D model, that is the whole idea… (CEO, timber frame builder)

Collaborative Maturity

Even though most designers in this project had replaced their 2D CAD system with object-based BIM technology, they did not prioritize collaborative design in this project. The architects and engineers occasionally exchanged modeling information, but the designers did not develop any routines for regular exchange of design information, nor did they assemble their models into joint BIM models. Thus, the designers' collaborative maturity in BIM-based design can be classified as "ad-hoc" (Succar et al., 2012). The following quote illustrates that the designers in this project did not arrange a routine for design exchange:

> In this project, we would have benefited from a slightly clearer understanding of how to interact (Fire-protection engineer)

DISCUSSION

In this section, we discuss our findings, focusing on commonalities and differences across the two projects studied. To guide the discussion, Table 3 presents an overview of each actor's enacted capabilities. Enacted capability refers to the actor's collaborative capability as displayed in the studied projects, since as we pointed out in the case presentations some designers did not deploy their full capabilities in this project. An overview of the key findings from both case studies is presented in Table 4. In our assessment, none of the participants in these case projects displayed collaborative capabilities of BIM Stage 3 or higher, as we did not identify fully integrated BIM practice and did not find evidence of any advanced virtual analysis conducted based on joint models. Thus, in both projects, there was room for improvement and intensification of collaborative practices. This finding is in line with research reporting that collaboration in construction projects is challenging, and that many critical advantages in BIM remain unexplored (McCuen et al., 2012).

Table 3. Actors' capability stages in the case projects

Capability stages	Pre-BIM status	BIM Stage 1	BIM Stage 2	≥ BIM Stage 3
Case (A) Library	➢Fire-protection engineer ➢Main contractor ➢Glue-lime builder ➢Client	➢Massive-wood contractor	➢Architect ➢Structural engineer ➢HVAC engineer ➢Electrical engineer	
Case (B) Residential project	➢Geotechnical engineer ➢Fire protection engineer ➢Client	➢Architect ➢Structural engineer ➢HVAC engineer ➢Electrical engineer ➢Timber frame contractor ➢Structural engineer for the wooden elements		

On the upside, more than half of the actors in our two cases used object-based BIM technology. Five out of nine actors in the library project and six out of nine actors in the residential project operated based on BIM technology. These actors had collaborative capabilities of at least BIM

Stage 1. All BIM-capable actors used their systems to speed up the production of 2D drawing sets, but only some decided to use modeling technology in collaboration. Thus, we found a predominant focus on 2D drawing production, which indicates that many actors left their old organizational processes intact, and approached BIM in terms of the older 2D CAD technology. This finding is in line with research arguing that users are likely to use new technology analogously to the old (Orlikowski & Gash, 1994).

Table 4: Key findings from the case projects

Collaborative performance under varying project complexity	
Capabilities	➢No fully integrated BIM practice has been established (BIM Stage 3 or higher)
	➢BIM widely used internally to speed up 2D paper drawing production (BIM Stage 1)
	➢BIM based collaboration prioritized in complex project (BIM Stage 2)
	➢BIM based collaboration not prioritized in simple project (BIM Stage 1)
	➢Not all designers have the capability and technology to participate in collaboration (Pre-BIM)
	➢Complexity of a project important driver for collaborative work at BIM Stage 2 or higher
	➢Significantly higher amount of planning work required when e-collaboration is prioritized (≥ BIM Stage 2)
	➢The business value of BIM-based collaboration for simple projects not perceived as significant (≥ BIM Stage 2)
Maturity	➢Lack of “know-how” for collaborative BIM work evident for both projects

Various actors continued to work based on their old Pre-BIM 2D CAD drawing technology, which excluded them from participating in BIM-based collaboration. This finding is partially explained by the fact that many interoperability issues among BIM and other advanced simulation software, such as Computational Fluid Dynamics (CFD) software and Geographical Information Systems (GIS), remain unsolved (Merschbrock & Munkvold, 2012). These issues prevented actors such as the geotechnical and fire-protection engineers from adopting BIM technology. Others, such as the general contractor in the library project, simply remain hesitant to adopt new BIM technology and deliberately continue to work based on Pre-BIM technology. This finding corroborates research reporting that the AEC industry is generally slow to adopt new technology (Gu & London, 2010).

In terms of collaborative maturity all actors working with BIM were comfortable using the technology for in-house design and to produce 2D drawings. However, most actors except the engineers in the residential case project lacked prior experience and “know-how” in BIM-based collaborative design. This lack of knowledge is explained by the industry’s current prevailing focus on internal processes rather than e-collaboration (Neff et al., 2010).

Despite the lack of know-how, four designers in the library project decided to prioritize collaborative design. Collaborating based on BIM allowed all parties involved in the project to understand the building’s unusual and complex form more readily. The architect found it “extremely valuable” to engage in e-collaboration, as it allowed him to share design ideas with clarity and rich detail. The engineers found that the “very special” nature of the building called for collaborative BIM use. Moreover, the engineers found that improved clarity in design information sharing was of particular importance to fit the building’s complex technical installations inside the wooden rib structure (Figure 1). Thus, collaborative BIM use was necessary and desirable for the architect and the engineers. Owing to their lack of know-how, the designers had to learn how to share their digital work while operating in an ongoing construction project. Their collaboration thus suffered from a lack of collaborative maturity. The designers needed to overcome various socio-technical challenges, including the development of a routine for collaboration and various technical problems inherent in their information infrastructure, which hindered them from achieving truly integrated practice.

The BIM-capable designers in the residential project decided not to prioritize collaborative design. Their technical base of BIM applications would have allowed them to create, transmit, and retrieve virtual models. However, they decided that extensive e-collaboration would not be required to accomplish this project. The engineers, who had prior experience in BIM-based collaboration, argued that this project was "quite simple" in terms of placing technical components, and that they had "a good feeling" not to engage in e-collaboration. They found that not focusing on collaborative design and not seeking to establish such collaboration allowed them to complete their design work faster. We observed that collaborative design was prioritized in the complex library project, whereas in the simpler residential project, collaborative design was not paramount. We conclude that the complexity of a construction project is an important factor influencing whether e-collaboration work is prioritized.

BIM-based collaboration has positive implications for design performance in construction projects, regardless of their size and complexity, and too little collaboration can lead to expensive mistakes even in small and simple projects (Hore, Montague, Thomas, & Cullen, 2011; Sebastian, Haak, & Vos, 2009). Others argue that "if higher levels of interactions between participants emerge [e.g., through full 3D BIM cooperation], companies in building projects will likely obtain […] higher cost benefits and less risk" (Grilo & Gonsalves, 2010, p. 530). Moreover, e-collaboration based on parametric modeling makes it considerably easier to materialize "curvy, non-orthogonal, non-regular [and] blobby," ergo complex, projects (Scheurer, 2010, p. 89).

However, our data show that BIM-based collaboration does not yield unconditional positive implications, especially for simple, non-complex projects such as the residential project. In such projects, the potential benefits of e-collaboration may not be considered significant enough to outweigh its drawbacks. Designers in simple projects may not want to spend time and money on trying to establish and maintain a functional digital collaboration when the design can be solved without it. In other words, collaborative capability will be enacted only in full if the business value of BIM is perceived as significant for the designers. Introducing e-collaboration in a construction project initially leads to a loss in design productivity for simple and complex projects, and that the productivity gains eventually achieved by the new way of working are larger in complex projects than in simple projects. Further, it is expected that e-collaboration will only become feasible for simple projects when the initial productivity loss can be contained.

Implications for Practice

We argue that current practice would benefit from a more structured approach to building business cases for e-collaboration to evaluate when it "pays off" to engage in e-collaboration given a project's complexity (Kristensen & Kjil, 2010). This approach will involve the following elements:

- First, practitioners should seek to understand the potential benefits of BIM and e-collaboration for their project. This could be done by sorting data on the benefits of collaborative BIM use in other projects similar in complexity. The benefits of prior BIM e-collaboration might for instance be measured based on IS evaluation techniques such as post-implementation reviews, balanced scorecard or similar (Merschbrock & Munkvold, 2012). In addition, indicators such as BIM's impact on scheduling, cost estimation accuracy, and the number of issued change orders, could be useful for understanding the benefits of BIM and e-collaboration (Hartmann, Gao, & Fischer, 2008; McGraw-Hill Construction, 2012).

- Second, the assessment of the individual designers' e-collaboration capabilities and maturity at project initiation is required to understand the effort it would take to establish a fully functional BIM collaboration. This evaluation could be done based on capability maturity assessment frameworks (Succar et al., 2012).
- Third, the resources required for e-collaboration (time, cost, equipment, personnel, etc.) must be estimated by all potential collaborators. Naturally, the accuracy of such estimates would benefit from available historical data collected in prior projects. In addition, more experienced firms are likely to need fewer resources in their collaborative work (Kristensen & Kjil, 2010).
- Fourth, a cost benefit analysis balancing potential benefits vs. required resources for BIM e-collaboration would aid practitioners to make better informed decisions and help to turn the perceived business value of BIM collaboration into an approximation of its actual business value.

Further, the findings suggest that a systemic approach to Collaboration Engineering (CE) in which engineers develop collaboration processes fit for a project's information needs and train practitioners to work accordingly is needed (Kolfschoten, van der Hulst, den Hengst-Bruggeling, & de Vreede, 2012). Large public and private construction clients (such as Statsbygg and Skanska in Norway) as economically predominant participants in the collaborative environment of many projects are important actors when it comes to engineering collaborative processes (Schroth & Schmid, 2009). However, currently only a few "enlightened" construction clients make the most of their design teams' collaborative intelligence (Owen et al., 2010). And unless clients consider the information needs of particular project situations and demand and prioritize BIM accordingly, the benefits of e-collaboration will not be attained (Merschbrock & Munkvold, 2013). The following areas require improvement:

- First, the current approach taken by large clients is to standardize BIM based e-collaboration in their projects by developing standard BIM manuals and contracts (Statsbygg, 2011). However, adopting a "one size fits all" approach to defining participant roles, generic model requirements, and e-collaboration deliverables may fit for some projects but may be unfit for others. We argue that a more balanced approach is needed to allow for a flexible response to complexity. This issue could be tackled by developing BIM manuals defining several levels of e-collaboration intensity that could serve as building blocks to engineer customized e-collaboration environments for individual projects. Further, building procedural guidance into the system may support the appropriation of integrated e-collaboration technologies such as BIM (Munkvold & Zigurs, 2006). This could take the form of features directing the users in their interaction with the system, and collaborative scripts supporting the team process (Briggs, de Vreede, & Nunamaker, 2003).
- Second, a practical implication of the findings is that institutions creating e-collaboration tools and standards, such as the industry-led buildingSMART alliance™, need to develop solutions suited for a range of project complexities to help make the AEC industry more efficient. However, buildingSMART™ members are foremost major construction firms and clients whose daily practice is concerned with large and complex projects (BuildingSMART, 2013). Thus, today's e-collaboration solutions are best fitted to address the challenges experienced by large firms in complex projects. Small and medium-sized enterprises (SME) must be included in these professional forums to develop e-collaboration solutions suited for simple construction projects (Sebastian et al., 2009). The need for e-collaboration solutions for simple projects is currently being overlooked.

All teams need a collaboration policy, and the designers and clients in a project team must agree on the context and rules for their collaboration (Hwang & Rotenstreich, 2012). In temporary undertakings such as construction projects, this requires a high degree of awareness and an "understanding of the activities of others, which provides a context for your own activity" (Dourish & Bellotti, 1992, p. 107, cited in Sultanow, Weber, & Cox, 2011). This could be done by establishing an organizing vision for the collaborative work and agreeing on the key functionalities of the inter-organizational system (Lyytinen & Damsgaard, 2011; Merschbrock, 2012). Indeed the "organizational structure required to support human e-interactions is central to efficient e-collaboration" (Rutkowski, Vogel, van Genuchten, Bemelmans, & Favier, 2002, p. 227).

However, especially practitioners who do not have prior experience need to build up know-how to be able to judge BIM's business value and to work based on BIM. Some scholars have suggested establishing government competency centers in which practitioners could learn about the new technology (Hore et al., 2011). Moreover, once a project team has agreed to work collaboratively, an organized approach to learning how to work based on the shared IS is needed. This could include courses on the systems used and the establishment of several BIM super users at the project level to support the designers in their work. A fully functional BIM-based collaboration will become possible only when all designers have equal knowledge on how to operate in the shared environment. Moreover, selecting the "appropriate sets of ICTs, structuring the group processes, building trust, and supporting decision-making" and providing everybody the same knowledge levels are essential to enable e-collaboration (Rutkowski et al., 2002, p. 227). Last, international industry-led organizations such as BuildingSMART®, established to develop interoperability standards and collaborative BIM work processes, could provide a useful resource for practitioners seeking to learn about BIM as collaborative tools.

Implications for Research

We have provided an initial conceptualization of the relationship between design productivity, project complexity, and e-collaboration. However, further research studying the interrelationship between project complexity and the actual business value of e-collaboration is needed to provide practitioners the opportunity to respond adequately to complexity.

Even though parametric modeling tools are useful for defining complexity, they do not make it disappear (Scheurer, 2010). Our findings illustrate that the practitioners opting for BIM e-collaboration experience several weaknesses hindering them from harvesting the benefits. First, collaborating with actors who not yet work based on BIM technology is challenging. Further research is needed to identify how these actors could be included in collaborative design despite their lack of appropriate systems and knowledge. Second, we argue that many actors, based on their demonstrated collaborative maturity and capability, still lack the necessary "know how" for sophisticated e-collaboration. Kristensen and Kjil (2010) argue that *effectiveness* and *efficiency* in e-collaboration depend upon knowledge of how to collaborate, mutual trust, and shared understanding. We argue that building stronger business cases for BIM use, based on a solid analysis of its actual business-value and considering project complexity, is the initial step in managing expectations about what can be gained by e-collaboration. This could serve as a solid foundation to establish trust and shared understanding among the collaborative partners.

CONCLUSION

We have shown that the intensity of e-collaboration in construction depends upon project complexity. Our analysis documents how designers engage in collaborative BIM design only if they perceive a clear business value of doing so. Even firms with sophisticated BIM capabilities and knowledge of BIM-based e-collaboration remain hesitant to engage in collaborative work when the immediate business value of such collaboration is not evident. By conducting a comparative analysis of two projects varying in complexity, we found that the perceived business value of e-collaboration increases with a building's complexity. BIM-based collaboration was regarded as "extremely valuable" in the complex project and as "too costly and unimportant" in the simple project. This leads us to conclude that BIM-based collaboration does not have unconditional positive implications for all types of projects.

In addition, we found that current practice could benefit from building solid business cases for e-collaboration taking into account a building's complexity. We suggest that current practice could be improved by conducting the following: 1) thorough assessments of BIM's potential benefits based on a project's complexity, 2) an assessment of all designers' collaborative BIM capabilities and maturity, 3) a reliable cost estimate for full-scale BIM e-collaboration based on capabilities and maturity, and 4) a cost benefit analysis that identifies the business value of BIM-based e-collaboration. Further, current practice could be improved by adopting a systematic approach to CE in which a collaboration environment is customized to facilitate the information needs of particular projects. In addition, there is a need for large professional clients to develop BIM manuals that could be used as building blocks for the custom collaborative environments. Last, national standardization bodies must develop BIM standards that provide different levels of BIM-based e-collaboration.

However, even when e-collaboration is prioritized, collaborative performance in most projects is still far from integrated practice. Various issues related to collaborative capabilities and maturity remain unsolved, including lack of know-how and organizational readiness for succeeding in BIM-based e-collaboration and inappropriate information infrastructures. We argue that current practice could benefit from a further dissemination of know-how about e-collaboration, and by the active inclusion of designers who do not use the technology. Our analysis has emphasized several weaknesses in current digital construction and suggested possible improvements for increasing e-collaboration performance based on BIM.

Our findings portray an ambitiously designed public project and a standard residential project. Although the case projects represent wider e-collaboration practice in the AEC industry in terms of project composition and the actors' digital modeling practices, our findings must be validated through further research on BIM's business value for different types of projects with differing complexity.

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Article 4

Merschbrock, C., & Wahid, F. (2013). Actors' freedom of enactment in a loosely coupled system: The use of building information modeling in construction projects. *Proceedings of the 21st European Conference on Information Systems (*ECIS), Paper 124, Utrecht, The Netherlands, 5–8 June.

ACTORS' FREEDOM OF ENACTMENT IN A LOOSELY COUPLED SYSTEM: THE USE OF BUILDING INFORMATION MODELLING IN CONSTRUCTION PROJECTS

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Abstract

Construction design is typically a collaborative effort involving multiple design professionals covering different areas of expertise. These professionals typically form 'loosely coupled' temporary project organisations for the duration it takes to accomplish their work. Even though construction designers operate in loosely coupled systems, their work tasks are highly interdependent. Additionally, the designers are interdependent in their use of technology and need to fuse and integrate their information systems (e.g. Building Information Modelling [BIM] systems) for the project's duration. The controversial situation of being highly interdependent in conjunction with having to operate in a loosely coupled system is discussed in this paper. These two characteristics of project-based work along with the notion of the actors' position in the process chain, are then conceptualized to have an impact on the actors' freedom of enactment in using a certain technology. However, the actors' freedom of enactment cannot always be directly transformed into constituted enactment. Instead, improvised practices emerge or actors simply decide not to constitute the possible enactment. We develop a conceptual framework to capture the interplay of the aforementioned concepts. As an initial validation, we test the plausibility of the framework using data from two construction projects that involve the use of BIM systems.

Keywords: *Building Information Modelling, BIM, construction project, freedom of enactment, loosely couple system.*

1 Introduction

Today's construction projects could not be run at the necessary speed without using advanced information systems (IS) such as Building Information Modelling (BIM). In this study, BIM is defined as 3D digital representations of all physical and functional characteristics of a facility (NIBS, 2007). Anticipated benefits of the BIM systems include improved clarity in design information sharing and the potential to streamline the construction design process ranging from early design negotiation and generation to execution. BIM systems are intended to provide a shared digital infrastructure to link heterogeneous, previously unconnected actors in a collaborative environment (Yoo et al., 2010). BIM technologies have the potential to serve as catalyst for innovation and improved inter-organisational processes (Berente et al., 2010; Boland et al., 2007).

Despite the increasing uptake of BIM systems, scholars report that design professionals still miss out on many of the crucial advantages the technology has to offer (Ahmad & Sein, 2008). There is a tendency for designers to use the new technology predominantly to automate old design processes rather than to substantially transform the way in which they communicate (Merschbrock, 2012). Not all actors are able to partake in BIM collaboration (Merschbrock, 2012) and especially those working at the 'periphery of a digital innovation networks' are frequently excluded from innovative practices

(Yoo et al., 2010, p. 3). Tales from the field support this claim and the following two quotes by professionals having used BIM technology in a joint construction project illustrate the problem:

> "We have been using BIM for some time and […] I am happy [with the system]. [In this project] I have not been forced in a very strict routine of drawing in Revit™, collision checking, and a full BIM kind of design process from the very beginning." (Architect)
>
> "There is a lot of rubbish you are not able to use. So in the end, you sort of only take over the geometry." (Timber frame manufacturer)

Basing upon the notion of enactment suggested by Weick (1988), we define the *freedom of enactment* as the degree of flexibility an actor possesses to perform actions in a given structure or to create new structure. For the purpose of our study we define structure as "a set of rules and resources instantiated in recurrent social practice" (Orlikowski, 2000, p. 406). BIM systems in construction projects can thus be considered a structure, as they embody social structures which presumably embedded into them by designers during their development and which are them appropriated by users when they interact with the BIM systems (Orlikowski & Iacono, 2001), and the use of BIM involves repetitive social practices carried out by various actors (Orlikowski, 2000).

The quotes above hint that the actors had different degrees of freedom when it came to technology enactment. From the first quote, we understand that the architect enjoyed his 'freedom of enactment' in using BIM systems. Whereas the second quote indicates that the timber frame manufacturer struggled to solve problems inflicted upon him due to prior BIM use limiting his 'freedom of enactment'. This is partly explained by the nature of inter-organisational work in the construction industry which is characterized by high level of task interdependence (Dubois & Gadde, 2002). On the contrary, construction projects are organised as temporary organisations which are considered loosely coupled systems (Dubois & Gadde, 2002). In such a system, its elements affect each other "suddenly (rather than continuously), occasionally (rather than constantly), negligibly (rather than significantly), indirectly (rather than directly), and eventually (rather than immediately)" (Weick, 1982, p. 380) – cited in Orton and Weick (1990).

In addition, previous studies (e.g., Gal et al., 2008; Merschbrock, 2012) in the context of construction projects find that the potentials of BIM are not fully exploited, partly because of lack of a shared organizing vision and 'automation islands'. In order to get its full potentials, these inter-organizational problems should be eliminated (Lyytinen & Damsgaard, 2011). But hitherto, these unsolved problems and their roots in collaborative work involving various actors and interdependent technologies, like BIM systems, are not properly understood. Instead of examining the phenomenon from a macro level (i.e., strategic/industry level) (see e.g., Lyytinen & Damsgaard, 2011), in this study we are particularly interested in understanding it from a micro level perspective (i.e., operational/project level). We expect that this effort will complement the stock of previous studies. Hence, the question addressed by this study is: *How does this contradicting situation in construction projects influence the actors' freedom of enactment in using BIM systems*?

To answer this question, we attempt to develop a conceptual framework and plausible arguments derived from extant literature. In doing so, we use data from two construction projects to provide illustrations and to undertake an initial validation of the framework.

This study is important for three reasons. *First*, the conceptualization of construction projects as both highly interdependent and loosely coupled seems to be taken for granted and unproblematic in literature (Dubois & Gadde, 2002; Gidado, 1996). However, when it comes to the use of BIM systems, understanding this contradicting situation may help addressing some challenges experienced by professionals in the field. *Second*, the actors' freedom of enactment in the context of information technology use in construction projects, both generally and concerning BIM use in particular, has received little attention. This notion is useful to explain various problems emerging in the collaborative work between the actors involved. *Third*, scholars have argued that BIM and its exciting potential for transforming a major industry such as building construction is an interesting artefact in need for further IS research (Merschbrock & Munkvold, 2012).

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The remainder of the paper will be structured as follows. Section 2 presents the conceptual premises of this paper, followed by an attempt to develop a conceptual framework in Section 3. Section 4 presents brief tales from two construction projects. The findings with practical and theoretical implications are discussed in Section 5.

2 Conceptual Premises

2.1 Characteristics of construction projects

Construction projects are very complex in their nature rooted in their uncertainty and interdependence (Gidado, 1996). The high degree of uncertainty stems from incomplete activity specification, unfamiliarity with local resources and environment, and the diversity of materials and people involved. Meanwhile, the high degree of interdependence results from the number of interdependent technologies, the sequential nature of processes, and the high division of labour typical for the construction industry with design professionals covering different areas of expertise (Gidado, 1996).

However, scholars argue that the construction industry can be seen as a loosely coupled system (Dubois & Gadde, 2002). Several causes leading to loose coupling are highlighted in the literature, namely causal indeterminacy, fragmented external environment, and fragmented internal environment (Orton & Weick, 1990). The construction industry is characterized to be highly fragmented in its nature and it is argued that IS may help to reduce this problem (Howard et al., 1989).

In addition, Orton and Weick (1990) unveil several direct effects of loose coupling, namely modularity, requisite variety, behavioural discretion. This is to some extent the case in the construction industry (Voordijk et al., 2006). Further, loose coupling may happen between individuals, organizations, activities, intentions, and/or actions. Loose coupling is not always regarded as negative and in many cases it is the preferred way of organising. Opting for a loosely coupled system can increase satisfaction, effectiveness, and adaptability (Orton & Weick, 1990). To sum up, construction projects are complex due to their high degree of uncertainty and interdependence, but at the same time, they are loosely coupled. This leads to a contradicting situation which will be elaborated next.

2.2 Enactment

We have defined *freedom of enactment* as the degree of flexibility an actor possesses to perform actions in a given structure or to create new structure. The structure can be used, misused, or not used by the actors in various contexts (Orlikowski, 2000). In the context of this study, by adopting an ensemble view of IT artefact (Orlikowski & Iacono, 2001), BIM systems can be considered as a structure, where actors to some extent have freedom to use BIM in a way they perceive contextually appropriate. Moreover, enactment can also represent an actor's response to emerging changes in structure. Thus, the action is shaped and being shaped by structure (Gioia, 2006).

Our notion of enactment is closely related to the notion of *technology-in-practice* proposed by Orlikowski (2000). She defines it as "sets of rules and resources that are (re)constituted in people's recurrent engagement with the technologies at hand" (Orlikowski, 2000, p. 407). In her study, technology is enacted in three possible ways dependent on the response of the actors: *inertia*, *application*, and *change*. Enactment in the form of *inertia* happens when the technology is used to reinforce and preserve status quo, by limited use of it. In this case, the actors may either avoid using the technology or engage in but a cursory manner (Boudreau & Robey, 2005). In the *application* enactment, the actors may use the technology in collaboration, individual productivity, collective problem solving, or process support. All these are intended to reinforce and enhance the status quo (Orlikowski, 2000). The enactment in the form of *change* is chosen to transform the status quo by making improvisations in technology use. The last type relates to the notion of improvised learning by Boudreau and Robey (2005). They defined it as "learning situated in practice, initiated by users, and implemented without any predetermined structure" (Boudreau & Robey, 2005, p. 9). Another type of

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enactment is introduced by Boudreau and Robey (2005), which is *reinvention*. It is defined as "unintended uses of technology in which users compensate for their limited knowledge of the system and perceived system deficiencies by developing 'tweaks' and 'workarounds'" (Boudreau & Robey, 2005, p. 9). Here, the invention or the technology is changed by its adopters after its original development (Johnson & Rice (1987) – cited by Boudreau and Robey (2005)). To sum up, actors' flexibility to decide what types of enactment they could choose under certain circumstances reflects the freedom of enactment. The enactment could manifest in various forms: inertia, application, change, and reinvention.

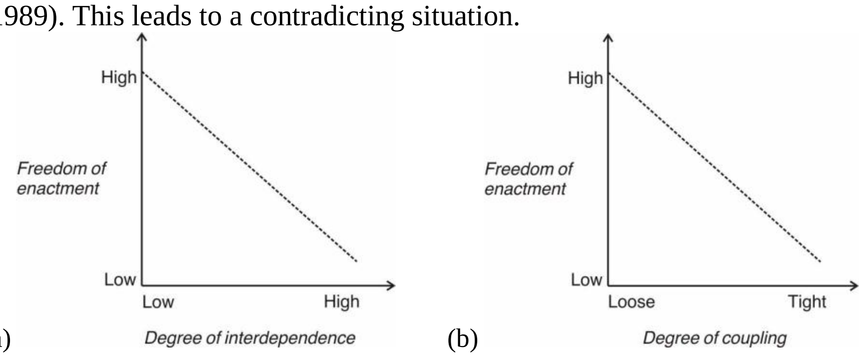
3 Conceptualizing the Freedom of Enactment

This chapter is concerned with advancing our conceptualisation of the freedom of enactment. We develop our conceptualisation stepwise beginning by discussing the contradiction between loose coupling and interdependence in systems. In doing so, we bring in the notions of interdependent and loosely coupled system and conceptualize their possible impact on the freedom of enactment. We argue that these notions are important to understand the context in which BIM systems are used. This is followed by a brief discussion of how an actor's position in the process chain relates to freedom of enactment. This discussion is important to understand the process at the micro level (i.e., operational/project level). Finally, we put forward a framework linking the aforementioned concepts, by introducing the notions of conversion factors that transform the freedom of enactment into constituted enactment.

3.1 Impact of interdependent and loosely coupled system on the freedom of enactment

In general, one would expect that actors' freedom of enactment is influenced by the degree of interdependence between elements constituting a system. The element could be a task, a technology or a person. In a highly interdependent system, actors' freedom to enact technology is low (see Figure 1(a)). In addition, we argue that the degree of system coupling may determine the actors' freedom of enactment. In a loosely coupled system the actors' freedom is expected to be high. Conversely, when the system is tightly coupled, the actors' freedom is limited (see Figure 1(b)). In a loosely coupled system, the types of enactment may be considered as the system's outcomes (Orton & Weick, 1990).

Figure 1 illustrates how both the degree of interdependence and the degree of coupling correlate negatively with the freedom of enactment. But, this is not always the case in the context of construction projects. Construction projects have been conceptualized as interdependent systems on one hand (Gidado, 1996), and as loosely coupled systems on the other (Dubois & Gadde, 2002; Howard et al., 1989). This leads to a contradicting situation.



(a) (b)

Figure 1. The relationship of (a) the actors' degree of interdependence; (b) their degree of coupling; and their freedom of enactment

We have argued in the Introduction section, that it is important to understand this contradicting situation. In doing so, at least two explanations can be provided.

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First, in the context of BIM use, one possible way of explaining the contradicting situation is by distinguishing between *task* interdependence and *technology* interdependence (Bailey et al., 2011). The former deals with the interrelationship of what the actors do in a broader sense (such as making a building design, an electricity installation plan), while the latter concerns with the interrelationship of the technologies used to perform tasks. Bailey and colleagues (2011) found that these different types of interdependence require different degrees of coordination. They concluded that high levels of task interdependence may call for high coordination, but high levels of technology interdependence may not necessarily do so. They also revealed that managers' policies around technology interdependence are not directed at managing the use of technology more efficient, but to manage the work accomplished by the technology. This finding seems to assume that there is a clear-cut separation between technology and work. In the context of collaborated work in construction projects involving a set of interdependent technologies along the way, the finding needs to be rethought. Could the absence of a focussed managerial response to technology interdependence explain why the actors working in 'the periphery of digital innovation networks' are frequently excluded from innovative work? A systematic study is required to answer this question.

Second, another way to understand this contradicting situation is by contrasting project and industry level of analysis. Dubois and Gadde (2002) argue that complexity of construction projects is managed through tight couplings among the firms, by relational exchange and inter-firm adaptations. But, this is not the case in the construction industry. Further, they assert that in the construction industry, there are few inter-firm adaptations beyond the scope of individual projects, and the involved firms tend to rely on short-term market-based exchange (Howard et al., 1989). Here, it is expected that there is a tight coupling among the firms. But in a larger context of permanent firms network, at industry level and beyond short-term construction projects, the coupling is loosened (Dubois & Gadde, 2002).

3.2 Impact of the actors' position in the process chain on their freedom of enactment

Effects of loose coupling may be functional or dysfunctional (Weick, 1976). The question is then functional or dysfunctional for whom? One way to address this issue is by making a distinction between recurrent and sequential systems, and considering the actors' position in the process chain.

In a recurrent system, where a process may go back and forth several times between the actors, the degree of interdependence between them is high along the way. At the same time, the system can be assumed to be tightly coupled. Hence, the actors' freedom of enactment is managed and constrained from the very beginning. Although it is still possible that the degree of freedom of the actors at the early stage of the process chain is somehow higher than that one of the late actors, it will not be significantly different.

The sequential nature of the supply chain in construction projects, where (1) architects explore aesthetical solutions; (2) consultants explore technical solutions; and (3) contractors build the specified product, is seen as a root cause for poor communication resulting in costly rework and unproductive downtime (Love & Li, 2000). In a sequential system (such as a construction project) with limited recurrent processes between the actors, the degree of interdependence varies along the process.

The actors in the early stage of the process depend less on the actors in the subsequent stages, while the actors in the late process chain depend greatly on the previous ones. This degree of dependence affects the actors' freedom of enactment.

To sum up, a loosely coupled system may be functional for the early actors, but dysfunctional for the later ones. The relationship between the position of the actors in the process chain and their freedom of enactment is depicted in Figure 2(a). In either case, the freedom of enactment is *tunnelled* as the project progresses (Figure 2(b)).

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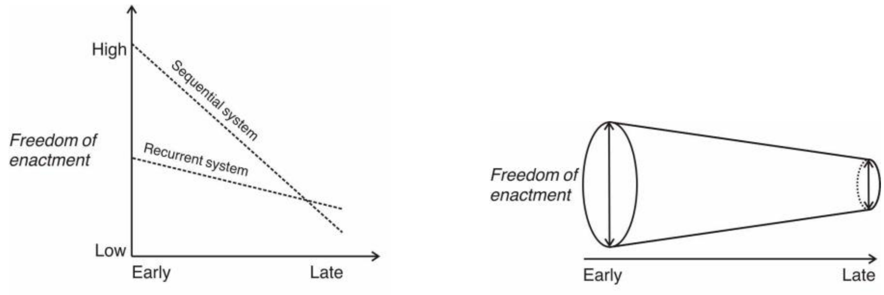

(a) *Actor's position in the process chain* (b) *Actor's position in the process chain*

Figure 2. (a) The relationship of the actors' position in the process chain and their freedom of enactment; (b) The freedom of enactment tunnelling

3.3 Freedom of enactment and constituted enactment

This part is inspired by the notion of capabilities and functionings in the capability approach by Sen (1999). We argue that this notion provides insights how the actors' freedom of enactment is transformed into constituted enactment. A *capability* reflects a person's ability to achieve a given functioning ('doing' or 'being'), while *functioning* is an achievement of a person: what she or he manages to do or be. Not all capabilities can be transformed into functionings.

This transformation is facilitated by a set of conversion factors, which can be personal, social, or environmental conversion factors (Robeyns, 2005). Personal conversion factors are factors internal to the persons using information systems. The personal conversion factors suggested by Robeyns (2005) include physical condition, skill, knowledge, and education. The social conversion factors are inherent in the society in which a person lives. Examples of social conversion factors include public policies, social norms, societal hierarchies, and power relations. Environmental factors emerging from the physical or built environment, in which a person lives, include geographical location, climate, the availability of tools, and the presence of infrastructure.

In the context of this study, freedom of enactment can be considered as capabilities of a person or a firm. The freedom of enactment cannot always be constituted into an actual enactment. Or, the actual enactment, which can be seen as functioning, may be manifested in various forms (i.e., inertia, application, change, and reinvention). In this study, we call it *constituted enactment*. The forms of constituted enactment are dependent on a set of conversion factors. The relationship between the degree of interdependence, the degree of coupling, the actor's position in the process chain, the freedom of enactment, and the constituted enactment is depicted in Figure 3. Assessment metrics such as the Software Capability Maturity Model (CMM©) by the Software Engineering Institute (SEI) could proof helpful to understand the *constituted enactment* in collaborative BIM use.

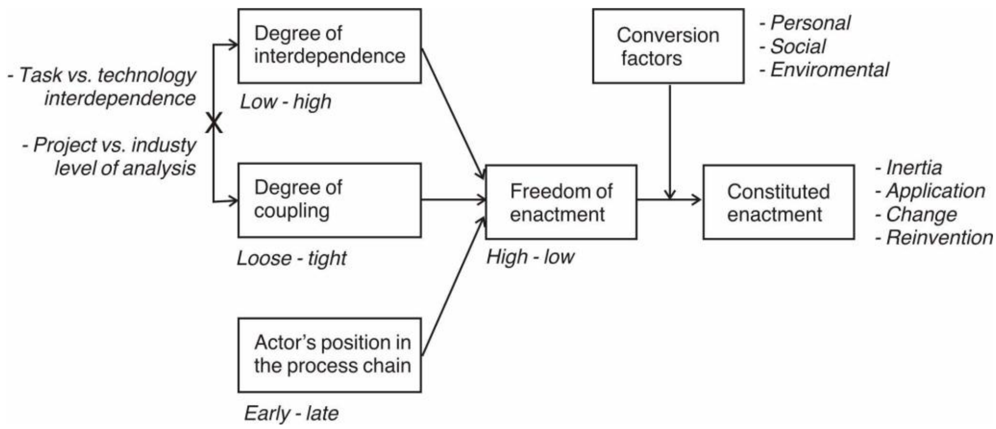

Figure 3. The conceptual framework

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4 Two Tales from the Field

Norway's wood-based building industry has witnessed heavy investments in automation and technologies such as BIM. Recent legislation in Norway such as new standards for developing low-energy and passive houses and clients pressuring for reasonable quality create a need for new technologies and innovation. We find that this part of the Architecture, Engineering and Construction (AEC) industry striving for better integrated practice makes a compelling context to test the plausibility of our conceptual framework. For this reason, we do not provide thick description of the cases that are reported in detail somewhere else (Merschbrock, 2012).

The data has been collected based on 19 semi-structured interviews with design professionals. These design professionals worked on two different construction projects, a residential and a library project and the interviews were taken over a time span from September 2011 to May 2012. We expect that the cases represent different situations in the construction industry with regards to the actors involved and actors' digital modelling practices. Table 1 summarizes the professions of the informants interviewed. By choosing interviews as means for data collection we aim on gaining an understanding of the phenomenon by asking those experiencing it. The projects were carefully chosen based on three selection criteria: (1) the project participants should resemble a rather typical project constellation in the construction industry (e.g., client, architect, engineers and contractors); (2) the design stage had to be completed at the time of data collection; and (3) BIM technology had to be deployed in construction design. The criteria were selected, to be able to provide a holistic account of construction design activity, to understand the perspectives of the actors involved typically in such activity and, to place BIM, as technological artefact at the core of our study.

First tale: Residential project	***Second tale: Library project***
Timber frame builders (CEO/design manager/production manager/drafter)	Engineering design manager
Engineering design manager (for HVAC, structural, electrical)	Structural engineer
Geotechnical engineer	Electrical engineer
Fire protection engineer	Fire-protection engineer
Client representative (CEO)	Massive wood builder (project manager)
Structural engineer for wooden structures	Glue-lime builder (project manager)
Architect	Client representative (municipality)
	Architect
	General contractor

Table 1. The profession of the 19 informants interviewed

4.1 First tale: Residential project

The residential project was a construction project initiated by a private property developer and encompassed the construction of three apartment buildings, which consisted of one hundred individual apartment units altogether. The architect aided the client in developing the requirements for the building at an early stage in the design process chain. The architectural work did neither depend on previously accomplished tasks nor on prior used technology. The client was indifferent which design technology was to be deployed in the project as long as the building would *"look new and modern and so on"* (Client, CEO). In this respect, the architect's early position in the process chain and his task and technology independence allowed him to enjoy a high degree of freedom when it came to deciding which design technology to use and how to accomplish the design work. Moreover, the architect had modelling systems in place and he was an experienced user of this technology. Thus, he could deploy technology in the way he "*liked to do it*" (Architect).

The favourable combination of freedom of enactment and task and technology independence, accompanied by appropriate conversion factors resulted in the enactment of 3D Sketching Software and architectural BIM software. The architect opted for using 3D Sketching Software as it enabled him a dynamic way of communication based on *"...snapshots of [his] model to show what [he] was thinking"* (Architect). In addition, he decided to deploy architectural BIM software as an internal tool to create 2D drawing sets. He decided, however, not to actively seek model based collaboration because he did not want to:

> "…force everybody into a specific way of working, which would maybe be strange to them [engineers and builders], or where they would not have experience from before" (Architect)

Engineering consultants providing the structural, electrical and mechanical design came second in the design process chain. Their task included building on prior design provided by the architect, accordingly they were moderately task and technology dependent. The engineers were limited in their capacity to use their modelling technology in collaboration. This was due to the architects' preference to use 2D drawings instead of digital models in collaboration. Thus their freedom to enact the cooperative capability of their modelling systems was limited. In consequence the engineers did not seek model based collaboration and decided to communicate with others based on 2D CAD drawings. Additionally, they were constrained in their available resources (conversion factors), hindering them to make effective use of their modelling systems:

> "It's not that difficult [to collaborate in BIM], you have to be a little more precise, and you need a little more effort. […] The clients have to be willing to pay for the extra work we do." (Engineer, Design Manager)

The actors involved in the late stages of the process chain, such as the timber frame builders, depended on design work produced by the architects and the engineers. Thus, they were task and technology interdependent. The following quote by a timber frame builder delivers evidence for the task and technology dependency:

> "I translate in fact the information from architects and civil engineers developing this building to production — to the carpenters working in our production." (Timber frame builder, Drafter)

The timber frame contractor has been significantly constrained in his freedom to work with BIM technology, as indicated by the following statement:

> "In fact the architect is not modelling in the kind of modelling which I need. The interfaces today do not deliver the kind of cubes and other volumes I need, so I have to decide in the beginning if I want to start now with a lot of information which is not usable in the same program. Or, if I try to find out what is the sense of this and start to model it new." (Timber frame builder, Drafter)

4.2 Second tale: Library project

The library and cultural centre was a construction project initiated by a local municipality in southern Norway. The project comprises the construction of a café, meeting places and administrative areas. The building's wooden structure consists of 27 ribs made of prefabricated glue-laminated timber elements and Computer Numerical Control (CNC) cut plywood boards. The design of the library can be considered ambitious with the ribs gradually shifting shapes resembling hybrid structures.

All architecture begins with a blank sheet of paper and architects are the first to draw a line on that blank page. Thus, the architect occupied an early position in the process chain of the library's design. Owed to this position, the architect's degree of task and technology interdependence towards others in early design was low to non-existing. The only task interdependencies which could be identified were loosely formulated needs, or desires voiced by the client such as to "*create the new cultural heart of [the municipality]*" (Architect). Thus, the architect was theoretically, at project initiation, free to use or enact whatever technology he felt was necessary to accomplish his work. Apart from having the freedom to enact technology, the architect had modelling technology and a team of co-workers possessing the skills and knowledge to operate 3D systems in place:

> "…we [architectural team competent in using several types of 3D programs] are able to work closely together and we can make use of the resources we need in the projects" (Architect)

The favourable conditions encompassing a high freedom of enactment and a wide availability of conversion factors resulted in the constituted enactment of three types of Building Information Modelling technology, namely: (1) rendering software to create 'photo realistic' 3D geometric elements signifying the future outer shape of the building; (2) architectural Building Information

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Modelling software to create detailed 3D architectural models; and (3) sketching software for creating 3D sketches.

Through the course of the library project the architects consulted with engineers to make sure that their design was structurally sound, buildable and complied to building codes. The engineers became involved about mid-way into the design process chain. Inherently, the engineers were moderately task interdependent in their work by having to extend and improve prior created architectural design work. Additionally, they were moderately technology dependent since they were required to work with modelling data created in architectural systems. At the same time they were loosely coupled to the architect as a member of the temporary project organisation. The technical interdependence resulted in interoperability challenges ultimately leading to 'workaround' practices. An example for improvised practice was the need to create compressed digital replicas of the architectural models to be able to use them in further work. We argue that the engineer's freedom of enactment was moderate. Ultimately the engineers enacted all their design systems as intended, however they had to conduct some time consuming workarounds. However, the engineers had some deficiencies rooted in social conversion factors, especially with hindsight to the skills required to work with compressed replica models:

> "…this was the first project where we tried to use BIM both based on IFC [the compressed files] and to change our process and I think we succeeded the first half [of the project] and then maybe not the second half." (Engineer, Design Manager)

Several actors involved in late stages of the process chain worked with creating shop designs related to either off-site manufacturing or on-site assembly of the building's parts. The massive-wood contractor fabricating the CNC cut plywood parts of the building serves well as an example for this group of actors. The massive wood contractor was highly task-dependent, as he had to build upon all prior executed design work ranging from architectural to engineering design. Moreover, he was highly technology-dependent, as they had to combine and make sense of modelling and drawing data created by various organisations and in significantly different design systems. This high degree of interdependence resulted in organisational and technical tensions and challenges. In the case of the library project the massive wood contractor improvised and developed workarounds to be able to make at least to some extent use of his advanced modelling systems and CNC machinery. However, they did not quite succeed gathering all prior created design data and decided for just using the structural engineering model in their design. This practice resulted in additional working hours and led to inaccuracies in the produced timber elements. We argue that the massive wood contractors had far less freedom to make efficient use of their technology than their predecessors. The following statement confirms that the massive wood contractor did not succeed in gathering the relevant data:

> "If the timber structure would have been drawn in our program we could have produced all the drawings, everything that we needed." (Massive wood builder, Project Manager)

4.3 Lessons from the tales

From the two tales presented above, we contend that the task interdependence between actors in design, planning, and construction is high. However, as a sequential system with a limited number of recurrent processes, the notion of task and technology interdependence might be interpreted in a different way. As expected our findings show that the actors in the early process chain (i.e., architects) are less dependent on the subsequent actors. Engineers who translate the design depend on the architect's work. At the end of the process chain, the manufacturers rely heavily on the work of the architects and the engineers. We call this situation 'backward interdependence', to differentiate it from 'reciprocal interdependence' when the degrees of dependence among the actors are rather similar. This finding differed from a common understanding arguing that construction project is reciprocal interdependent, but it is not the case of BIM use in the two projects under our study. The two quotes presented in the opening part of this paper illustrate it.

We got evidence that lack of coordination in a highly technology interdependent context creates harmful effects, specifically for the actors late in the process chain (i.e., glue lime manufacturer and massive wood manufacturer). The later actors expected that the design made by the architects and the engineers could be translated directly into the manufacturing process, but this was not the case. Inappropriate use of the BIM systems by the early actors limited the freedom of enactment of the later.

To tackle with this limited freedom of enactment, we found the later actors undertook ‘workarounds’. The digital work from the early actors who used BIM systems, was only used partly by the later. In this regard, from the first tale we found that the architects adopted the *inertia* constituted enactment as they used 2D CAD drawing. They avoided using the BIM systems or engaged in but a cursory manner (cf. Boudreau & Robey, 2005). A different finding was spotted from the second tale, when the architects attempted to use the BIM system to a great extent. Here, they adopted the *application* constituted enactment (cf. Orlikowski, 2000). In addition, in general, we found that the later actors (e.g., engineers, glue lime manufacture, and massive wood manufacturer) chose the *change* constituted enactment by making improvisation in the technology use (Boudreau & Robey, 2005; Orlikowski, 2000).This initiative led to a costly production, due to additional working hours allocated and possible errors detected during the loosely coupled process. Without the availability of skilful workers and some degree of tolerance in various aspects (e.g. monetary resources, time and technology), these ‘workarounds’ are not possible options. We did not find any constituted enactment in the form of *reinvention* from these two tales.

Based on the tales, we were able to pinpoint several conversion factors leading actors to exercise their freedom of enactment and turn it into constituted enactment. We found that actors’ decisions about which technology to enact in practice were led by their perceptions about which way of working would be appropriate in a given situation.

For example, the architect in the first tale stated that he used technology in the way he ‘liked to do it’. Further, we found that objectives such as ‘creating a dynamic way to communicate’ or ‘creating an ambitiously designed building’ influenced the actors’ decisions about enacting technology in practice. We argue that the aforementioned conversion factors stem from the social environment in which the action takes place. Beyond the social conversion factors related to the way in which actors liked to do their work, we found that factors internal to the persons using the technology, such as skills, experience, and education in using BIM, translated into constituted enactment. In addition, environmental factors such as having appropriate BIM systems, monetary resources, and time flexibility resulted in constituted enactment.

5 Discussion

The findings are, on one hand, in line with the study by Bailey and colleagues (2011) as the early actors perceived that coordination in the context of technology interdependence was unnecessary. On the other hand, this study extends their work by explicating the problems of unnecessary coordination related to the freedom of enactment, especially for the actors involved in the later stages. We identified a set of antecedents and impacts of freedom of enactment. Alike, we also unearthed several conversion factors which may play a role in transforming the freedom of enactment into constituted enactment in various stages of the projects. In addition, this study also provided new insights how to understand the contradicting situation in which a construction project at the same time is both interdependent (Gidado, 1996) and loosely coupled (Dubois & Gadde, 2002). In the following, we discuss the implications of our study both for research and practice.

5.1 Implications

Implications for research. Our conceptual framework provided new insights or understanding of the antecedents and impacts of freedom of enactment, particularly in the use of BIM systems. As an initial validation, we used data from two construction projects to test the plausibility of the framework. However, our lists of both the antecedents and impacts are not exhaustive. In this regard, we also briefly introduced the notion of ‘freedom of enactment tunnelling’. We found that the actors constituted different enactment forms along the process chain. For example, the architects in two

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different construction projects preferred different constituted enactment forms (in this study, *inertia* and *application*) when it came to the BIM use. However, our data did not allow us to analyze this finding further. Hence, further research, in addition to validating our findings, should seek to identify other possible antecedents for the freedom of enactment that partake in its tunnelling and the associated impacts.

Additionally, we offer new conceptualization of the notion of interdependence. Instead of seeing it as ‘reciprocal independence’, we propose to use ‘backward interdependence’. This notion then can be used to further understand the notion of loosely coupled systems in the context of construction projects. These notions (i.e., freedom of enactment tunnelling, backward interdependence, and reciprocal interdependence) could be detailed and specified further in other research. For example, further research could examine the freedom of enactment in a system with a high reciprocal interdependence. How does the process of tunnelling happen? How do the actors deal with that situation? What other factors (e.g., institutional factors) form the freedom of enactment?

One way of addressing it is by bringing in other relevant theories, such as institutional theory – specifically on the discussion of strategic response (Oliver, 1991) – or stakeholder theory (Mitchell et al., 1997) – in particular to see the power relation between the actors; and conducting systematic research in contexts with various characteristics (such as sequential vs. reciprocal systems).

Implications for practice. Our study also has some implications for practice. First, it provides insights for practitioners to understand better the issue of freedom of enactment of the actors involved in the projects. They can use our findings to determine policies how to cope with the problems. Possible recommendations include bettering coordination in terms of BIM systems use. Another practical recommendation is to increase the awareness of the actors involved in the early stages of the projects to think about possible problems they might inflict upon others by inappropriate or careless use of BIM systems, especially when the digital works are passed over to the later actors.

In addition, our study also offers insights about how to tackle the limited freedom of enactment experienced by certain actors. The tunnel of freedom of enactment can be ‘opened out’ to provide some more room for creativity enabling certain actors to constitute enactment. This can be done by performing ‘workarounds’, for example, by loosening the tolerance in terms of financial resource, man-hours, raw material, or even the (aesthetic) quality of the project.

5.2 Concluding remarks

When reading the paper’s title, one may expect at first sight that the actors’ degree of enactment in a loosely coupled system is high. But this is not the case for all actors in the context of BIM use in construction projects, due to some factors discussed above. One may ask, would the freedom of enactment be different, if the actors would use traditional, pen and paper-based tools? It could be similar, but our concern here is how to exploit the potentials of BIM systems by better understanding the actors’ freedom of enactment. Arguably, failing in managing this issue will hinder an effective inter-organizational collaboration that enables exploitation of benefits offered by BIM systems. Our hope is that our preliminary conceptualization of the freedom of enactment can be validated, fine-tuned, and extended by future research. By doing this, we expect that the notion of freedom of enactment can be used to better understand various problems emerging in collaborative work involving various actors and interdependent technologies, like BIM systems.

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Article 5

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IMPROVING INTERORGANIZATIONAL DESIGN PRACTICES IN THE WOOD-BASED BUILDING INDUSTRY

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Abstract. *Organizations operating in the wood-based building industry struggle to reap the potential benefits of Building Information Modeling (BIM) and Computer Numerical Control (CNC) technology. To identify what changes will be required to improve the use of BIM as a collaborative design tool, we conducted a focus group discussion with design professionals in the wood-based building industry in the Agder region of Norway. The workshop participants represented multiple disciplines, i.e. architects, engineers and manufacturers. The main identified barriers to effective use of BIM were low organizational BIM capability, ill-defined data exchange processes, and lacking demand and priority from the clients for including BIM in the project costs and schedule. To overcome these barriers, several changes were perceived necessary: services should be established where experienced BIM users aid the less experienced collaboration partners in creating digital models; guidelines for inter-organizational BIM-based design should be customized for the needs of the wood-based building industry; the role of a central BIM manager should be established; and knowledge on the application of BIM and CNC in wood-based building projects should be disseminated to clients and practitioners.*

KEYWORDS: Building Information Modeling, BIM, digital collaboration, design practice, building construction

1 INTRODUCTION

In the Agder region of Norway, timber has a strong position in comparison with other materials when it comes to the construction of detached houses and other small buildings. Moreover, timber has become an increasingly popular material for larger buildings and buildings spanning several floors. Examples of this trend include ambitiously designed structures such as the Kristiansand concert hall 'Kilden' or the new library in Vennesla. Thus, the wood-based building industry is an important actor for creating and retrofitting the regions' building stock. Recent legislation in Norway, such as the NS3700/01 standards for developing low-energy or passive-houses, and clients pressuring for reasonable quality standards, better architecture, and at the same time affordable housing, pose challenges to organizations working in the wood-based building industry (Schmidt, 2009).

The changing market expectations towards more affordable, attractive and modern buildings, fulfilling demanding energy and environmental standards, require organizations to rethink their way of working. Especially, improved collaboration becomes important as "monolithic, self-contained, inwardly focused corporations" (Tapscott & Williams, 2007, p. 290) will not be able to meet the market's expectations. Integrated design and building processes, and more sophisticated information and communication technology (ICT), have become highly focused topics to advance the wood-based building industry (Schmidt, 2009).

Recognizing the need for change, many manufacturers of timber-based building components have invested heavily in automation. Such investments include computer numerical controlled (CNC) machinery and Building Information Modeling (BIM) systems providing machine readable files. BIM is regarded by many as a core technology to ease the collaboration among the actors in the industry, to improve the build quality and to be a source for more innovative products (Bysheim, 2012). Given that Agder's wood-based building industry has witnessed heavy investments in automation and technologies throughout its entire supply chain, this part of the architecture, engineering and construction (AEC) industry makes a compelling context for our study.

Despite an increasing uptake of BIM and CNC, the timber industry utilizes their new BIM technology and CNC machining units foremost to simply speed up the production of simple timber frames or trusses (Larsen, 2008; Scheurer, 2010). Merely substituting old technology and leaving old organizational processes intact, is one reason for why parts of the industry are missing out on the prospective benefits of technological innovations (Merschbrock, 2012). Moreover, information sharing across organizations in BIM-based design remains an important challenge (Merschbrock & Munkvold, 2012). We seek to contribute to understanding how these challenges might be overcome by exploring the following question: *What changes will be required to improve BIM-based design practices among AEC professionals in the wood-based industry?*

To address this question we conducted an industry workshop involving a group of design professionals working hands on with the design of wooden structures based on BIM technology. The workshop was designed to offer a platform for practitioners to discuss experiences with BIM technology and how current practice could be improved. The paper presents the insights from this workshop, and discusses the potential implications of these.

2 RELATED RESEARCH

Three levels of analysis can be identified in the literature on BIM adoption and use: industry-wide, organizational and inter-organizational. The industry-wide BIM adoption studies seek to reflect on BIM adoption at national or international level (McGraw-Hill Construction, 2012). The organizational level studies focus largely on the behavior of single adopters of BIM (Peansupap & Walker, 2006), and the inter-organizational studies focus on the collaborative interaction of several adopters in project teams (Merschbrock, 2012). Much of the scholarship on BIM adoption to date has been focused on the technical requirements of BIM and the definition of new standards for information exchange, but less on the inter-organizational practices surrounding the modeling activity (Dossick & Neff, 2011). Recent international R&D outlook publications by institutions such as the International Council for Research and Innovation in Building and Construction (CIB), argue for further research to define new collaborative processes across all project phases and between all actors in construction projects (CIB, 2010). This finding is echoed by research reviews arguing for the need to strengthen research on the inter-organizational collaborative use of BIM in construction projects (Merschbrock & Munkvold, 2012; Shen et al. 2010).

Inter-organizational studies draw from theories such as the boundary object lens (Gal et al., 2008; Neff, Fiore-Silfvast, & Dossick, 2010) and Actor Network Theory (ANT) (Linderoth, 2010). This stream of research documents the need for project teams to develop new communication processes for taking full advantage of the new BIM technologies (Dossick & Neff; 2010, Whyte, 2011). However, creating such new communicative processes linking several organizations is far from easy as various “forces and structures must be accounted for” (Dossick & Neff, 2010, p. 459).

There is a tendency for today's AEC organizations to rush “headlong into it [BIM collaboration] without making the proper organizational changes” (Oakley, 2012). However, using new BIM technology without changing processes results in designers working in isolation instead of collaborating effectively (Merschbrock, 2012; Neff et al., 2010). Researchers argue that organizations should start by using BIM just on a few handpicked projects in order to "design, build and test new processes", which could then be "incrementally improved across a number of projects" (Whyte & Lobo, 2010, p. 566). Moreover, to be able to manage collaborative processes firms would need "inspirational leader[s] who can navigate a complex yet disperse project hierarchy, acquire much needed information, and strongly represent the interests of his or her team at the project level" (ibid., p. 459).

The R&D program *det digitale byggeri* (Digital Construction) is a Danish government initiative established to increase and improve knowledge-sharing between the parties of the construction sector. One of the outcomes of this program is the '3D working method' which offers a categorization of activities required to create, exchange and re-use modeling data at project level (bips, 2007; Moum, Koch, & Haugen, 2009). The framework consists of six main activities in model based collaboration (Table 1). We apply the framework to classify the issues raised by the workshop participants into topic areas, to allow for a focused discussion of the areas in need for further improvement.

Table 1: Activities in BIM based design (adopted from bips, 2007)

Activity	Definition
Drawing production	Encompasses all modeling activity required to produce 2D construction design drawings, disciplinary 3D models and aggregated 3D models.
Exchange	Modeling cooperation between the parties.
Simulation	The simulation activity conducted by individual designers in their respective area of responsibility, such as climate, energy, strength, fire etc.
Consistency checks	Check of disciplinary models for overlap, collisions and occurrence of objects.
Visualization	Visualization of models projected on a screen to improve communication.
Quantity take offs	Extraction of data from models to obtain information from disciplinary models for cost estimates.

3 METHODOLOGY

A useful methodology to identify "usage or managerial issues related to technology, systems, and IT management" is the focus group research method (Belanger, 2012). Focus groups is a research method devoted to data collection based on group interactions and a topic determined by a researcher (Morgan, 1996). The strength of a focus group method is that it allows for discussions where participants both query each other and explain themselves to each other (Morgan, 1996). Thus, the focus group method is considered a suitable method for creating an in depth discussion about work processes and communication practices surrounding the BIM model. Focus groups can be distinguished from other forms of group interviews in that they are normally conducted with a homogenous group of 3-10 strangers in a formal setting (Morgan, 1996). Belanger (2012) argues that it is important to invite a group of strangers which are "experts" in the topic area. Moreover, he states that the moderator should introduce the topic to get everybody in the same mindset, and ask broad open ended questions to gain an understanding of the respondents' attitudes and opinions.

The targeted participants of our focus group were firms affiliated with the regional Agder Wood initiative (www.agderwood.no). Three of the invited firms responded and sent a good selection of practitioners to participate in the workshop. The participating practitioners were two architects, one civil engineer and a contractor working for a timber frame manufacturer. The participants all had a similar strong knowledge base in design based on BIM technology, working hands on with the technology. The engineer had BIM experience since 2003, the architects had worked with modeling technology since 2007, and the timber frame contractor had worked with modeling technology since 1998. In terms of the position in their firm's hierarchy, they all worked more or less at the same level. This allowed for open discussions with relatively equal participation by all involved. Involving four professionals from three different firms, our focus group was within the recommended group size (Morgan, 1996).

The discussion lasted for three hours. The session was voice recorded, transcribed and analyzed by using qualitative data analysis software (NVivo9). The focus group transcript documents were imported into the NVivo9 system. Then altogether eight nodes or data ‘tags’ were created including the six activities relevant in BIM based design (table 1). Further, we added two more ‘overarching’ categories for classifying the *possibilities to improve practice* and the *roles and responsibilities* required for this. The transcript was coded and the data segments sharing a similar theme were gathered together into overview reports, which then were subsequently used to present the findings within this article.

4 ANALYSIS

4.1 Drawing production

The participants discussed some persistent issues related to the production of drawings and the documentation of design results. The first issue discussed was that project participants often have different levels of capability when it comes to working in BIM. From the discussion emerged that the organizations working in the wood-based building industry can be roughly classified into three levels of ‘BIM capability’ (Succar, 2012):

- Pre-BIM capability: consists of organizations that still prefer using 2D CAD design technology over using BIM technology. This group of ‘non users’ is especially populated by small construction firms and small consultancies having little available resources. According to the workshop participants these actors are interested in preserving the “status quo” and seek to keep their established ways of working intact.
- BIM-Stage 1 capability: organizations are ‘novel’ users of BIM technology. Examples mentioned were timber-frame firms that just began to recognize and explore the potential of modeling technologies. This group of organizations has not yet fully developed the capabilities to participate in a functional BIM collaboration at project level.
- BIM-Stage 2 capability: organizations are ‘expert’ users of BIM. These organizations have been able to build up considerable experience in 3D modeling and BIM based design. These actors have both the experience and the resources to run a fully functional BIM system.

The following statement illustrates that many Pre-BIM and Stage 1 users of BIM technology participate in today’s projects:

> “There are many that do not think BIM is important and they continue to work in 2D. And almost all firms that I work with are still learning to do BIM, there are many projects that are still run in 2D and there are consultants that do not model either.” (Timber-frame contractor)

When discussing the implications of different capability levels for project practice, it emerged that the BIM systems’ overall functionality depends on how well those actors that do not have expert knowledge in BIM can be integrated in the process. One of the architects mentioned that it would be possible for architects and engineers to provide services beyond their usual design tasks, and aid small timber-frame contractors to create BIM models and workshop drawings. The timber frame builder argued that this assistance would not be welcomed by many element producers, as the production of workshop drawings requires unique expertise only available at the manufacturers. The following statement illustrates that many would regard this “service” as inappropriate:

> “I do not believe that you would find a single element producer that would like the architect to produce production drawings, they want to control those themselves.”(Timber-frame contractor)

Further, the timber frame contractor stated that especially firms’ already using sophisticated technologies to run their production have an interest in controlling the production of drawings themselves. The timber-frame contractor continued to explain that the utility of CNC machines could be increased further by streamlining the flow of BIM design data from the early design stages to production. He argued for a better coordinated information exchange, and made the case for more effective "channeling" of information towards the persons creating the workshop design and CNC data:

> "[If you have] a CNC machine that is a controlled by a 3D model and by data right out of the BIM model you can take it still further and have automated tools that produce ready walls. […] It is more demanding for the person that is supposed to draw the model, and he needs to know how things shall be, and he needs to be very knowledgeable. The knowledge of many individuals needs to be bundled within the one person that has to draw." (Timber-frame contractor)

4.2 Exchange

Practitioners experience a variety of issues related to the exchange of BIM models at project level. It emerged from the workshop discussions that especially the structured exchange of modeling data remains a challenge in construction projects. Practitioners find it difficult to arrive at a consensus about how and when in the project it would be appropriate to exchange modeling data. The civil engineer shared her experience, and the following quote illustrates that the lack of agreement for structured model exchange may lead to design faults:

> "Architects are really unstructured; when we began with the project it was really difficult to agree on the origin [for the axis lines X, Y and Z in the three-dimensional space], and it is of outmost importance to get this right if you want to combine [BIM] models. […] We experienced that a wood manufacturer used outdated [6 weeks old structural] models in their design, and that it took a huge effort to correct their design later on. In consequence, nothing fitted really 100%" (Civil engineer)

Another issue that surfaced in the workshop discussions was that today's commercially available BIM software solutions are considered technically inadequate for serving as collaborative workspaces in which several designers jointly create solutions:

> "I believe that today's programs do not provide the possibility to work in a shared model, it is still too early." (Civil engineer)

Instead of working in a shared model, today's practitioners exchange modeling data by creating replica of their models based on the Industry Foundation Class (IFC) file format.

In addition, the workshop participants stated that the client's demand is a crucial precondition for BIM design collaboration:

> "If the client does not want BIM then we do not work with BIM […] there will be no BIM if it is not specifically asked for. […] We draw in 3D, but what matters in BIM is the information that you put inside, and if they do not ask for that information then we do not use our money on that." (Architect 1)

From the workshop discussion, designers perceive the practice of BIM-based collaboration as more difficult and time consuming when compared to traditional design practice. Thus, the architect argued that if clients are not specific in their intention to run the project as a BIM project and do not allocate additional financial resources for the designers, then all parties would minimize their BIM related work efforts.

4.3 Simulation, consistency checks, visualization and quantity take offs

In today's projects it is fairly common that engineering consultants deploy simulation software to assess, for instance, a building's stability, electrical dimensions or to assess the fire resistance of a structure. However, according to the civil engineer these simulations are mostly run in separate simulation software external to BIM. Other simulations such as clash detections, environmental assessment and quantity take offs, are regarded as additional services for the client which will only be run when explicitly demanded. The following statement by the architect indicates this practice:

> "We have many small projects and we create 3D models all the time, but BIM and 3D modeling is not the same. BIM design is when you make use of all the possibilities it offers for quantity take offs, model checking and such things. These things are not often required, but large clients such as [a big Swedish contractor] and [a Norwegian public client] demand that. We have now a large project with [a multinational construction company based in Sweden] and they are quite advanced when it comes to quantity take offs and calculations." (Architect 1)

4.4 Possibilities for improving practice

The participants suggested a variety of possibilities for improving current practice. Especially the establishment of a set of rules governing the design process was regarded as a necessity to improve BIM based collaboration. These BIM exchange rules should define what everybody needs to do and know to enable a structured model exchange (e.g., technology used by the disciplines, type of models, the x, y and z coordinates of the design origin). Further, it was suggested to arrange for an early project meeting in which these rules should be formulated. To enforce the BIM exchange rules the practitioners suggested establishing a BIM quality control system at project level:

> "To get good coordination and to make a good system one could for instance run a quality system based on check lists and so on. This would make it clear for everyone what to do [when exchanging BIM models]." (Architect 1)

Further, the civil engineer stated that current contracts would need to be adjusted to be able to run a BIM project. Beyond establishing BIM rules, such a contract should be specific about the interfaces across organizations in BIM design work. The timber frame contractor argued that it would be challenging to define clear interfaces separating practitioners in their modeling work. However, there was agreement that current BIM contracts are not specific enough, and that the contracts need to offer more precision in their formulation to ensure that everybody can contribute to modeling.

One architect stated that firms could develop a more strategic approach to tendering by offering two cost estimates for their services. One of these estimates could include working in BIM-based design including intense collaboration and related managerial tasks, and the second could just include an estimate of "business as usual" standard architectural practice. This strategic tendering could enable clients to choose from the two options. Arguments for clients to decide for the more 'expensive' BIM alternative could be better ability to assess whether the proposed design solution meets the requirements, the ability to assess what the building will look like and how it will fit to the surroundings, benefits for operation and maintenance, better and more reliable cost estimates, and a reduced fault rate (bips, 2007). Another issue discussed was that all disciplines including the timber-frame contractors, should be included at an earlier stage in the design process to allow for their active participation in collaborative modeling:

> "All disciplines have to be involved earlier, for example most of the time we come in very late in the process, it is only in some large projects where we are involved earlier. We are then able

> to look at early BIM models and suggest changes that would include massive cost reductions for the client." (Timber frame builder)

There was consensus in the focus group that a building's design should be finalized in an appropriate time frame and before the on-site construction commences. Allowing designers to use more time for their design would have the effect that BIM models could be created with greater attention to detail, and in a higher quality than currently possible. However, this would require for clients to make design decisions earlier in the project. Clients would need to take decisions about the materials, the functionality and the aesthetics of the future building early on in the project. Moreover, after having finalized the BIM models the design should be "frozen", meaning that changes throughout execution should be limited.

In addition, the designers stated that working based on BIM is resource demanding, and that it would require clients to commit additional financial resources at an early project stage. However, the participants argued that these additional costs would be compensated for by higher product quality and less rework and faults during the construction phase:

> "The entire industry should use maybe 5% [of the total estimated costs] additionally in design, and they can easily earn that in by reducing faults on the construction sites." (Architect 1)

4.5 Roles and responsibilities

The focus group discussed how responsibilities and organizational roles would need to be arranged to optimize the structuring of the communicative processes in BIM. There was agreement that a central BIM management function would need to be established at project level to improve current practice. This management function should serve as a central BIM communication hub, taking care of the structured distribution of model based design data at project level. Further, this management function should be a control instance to enforce agreements about quality, interfaces and delivery time of disciplinary modeling contributions. The focus group suggested that this function should be filled by a senior project manager having technical understanding of the issues that may arise for individual disciplines. Several participants stated that this manager would need to take care that everybody gets an equal and fair treatment in the BIM collaboration, and to grant this fairness the manager should be independent of the disciplines involved in the project. Further, this manager would need to be able to spot weaknesses in organizational BIM modeling practices and introduce corrective measures. This would require a powerful actor or somebody having the legitimacy required for effective management. Moreover, this person would need to have sophisticated communication skills to be able to create an environment in which designers feel comfortable to share their designs. One issue raised was that the establishment of a central BIM manager role would require suitable funds and that this solution might be appropriate for large projects, but less so for small residential projects in which funds are relatively limited.

5 DISCUSSION

The focus group discussion allowed for developing ideas for a managerial response to the currently experienced issues related to BIM design. According to the focus group members, this response would create the possibility for better practice. An overview of the key findings is presented in Table 2. We found that many specialist contractors operating in the wood-based building industry have invested heavily in new CNC machinery and BIM software.

However, the current use of this machinery is limited to producing simple timber-based building components such as trusses and frames not requiring intensive 3D modeling efforts.

Table 2: Possible Improvements for BIM based design

- Disseminating knowledge about BIM among the actors in the industry by establishing a regular discussion forum joining academia and practice
- Establishment of criteria for structured model exchange at project level
- Establishment of the role of a central BIM manager distributing, assessing and managing the design at project level
- Channeling the information flow towards the designers producing CNC machine data
- Definition of the interfaces and scope of disciplinary designs contributions
- 'Expert' BIM users could actively support 'novel' and 'non' BIM users in the project's design
- BIM start-up meeting in which everybody participates
- Establishment of a BIM model quality assessment system (e.g. shared model origin x, y and z)
- Precisely formulated BIM contracts
- Early involvement of all actors including the timber-frame builders
- Finalizing the design before construction commences
- Allocation of additional financial resources or towards the design stages
- Getting the client's "buy in" for BIM and the resources required for a fully operational BIM system at project level
- Close managerial attention needs to be directed at BIM collaboration
- Design decisions have to be "front loaded" to enable BIM

However, many of these firms begin to explore the possibilities for producing more advanced architectural elements based on CNC data, and to cope with the increasing complexity of the elements they need to create or acquire more machine readable 3D data.

Our findings illustrate that such accurate 3D production data is hard to come by for wood-based building firms in current practice. Current modeling practice at project level is "messy", as actors in the industry continue to struggle both with production and exchange of model based data. The difficulties to produce models result from different organizational capabilities with regards to BIM use. The firms exist along a spectrum ranging from highly computer literate expert BIM users to non-users of BIM technology. This finding is in line with earlier research, and BIM maturity and capabilities remain highly focused research topics (Succar et al., 2012). Many of the current difficulties to exchange BIM models can be attributed to a lack of structuring of the communicative processes required (Merschbrock, 2012).

We argue that both BIM capability and the communicative processes are areas in need for managerial attention. The exchange of BIM models could be eased by establishing better formal arrangements defining the scope and level of detail of modeling work for each discipline. And when adjusted for wood-based building, guidelines such as the Danish "3D working method" could be useful to improve practice.

Beyond formal arrangements, real improvements come only within reach if stage 1 ('novel') and pre ('non') BIM users are actively included in the design. One approach could be to mitigate the lack of BIM skills at project level by providing firms with external help. In addition, all parties should be given an appropriate time-frame to create their designs. In recent literature, time pressure is seen as: "*an important barrier to the successful use of interorganisational ICT* [such as BIM]" (Adriaanse et al. 2010, p. 79). First, BIM design requires more work than traditional design and thus the timeframe for BIM design should be extended. Second, all parties including the timber-frame designers need to be included earlier in design. The importance of early contractor involvement in the design process to improve drawing quality has been recognized in literature (Song et. al 2009). Third, the client's decision making would need to be 'frontloaded', meaning that more decisions have to be taken at an earlier stage.

Our findings suggest that the inter-disciplinary modeling work should be run by a central BIM manager. In addition, BIM needs to be managed within individual organizations participating in the project by strong and inspirational local BIM managers (Dossick & Neff, 2010). The central manager could facilitate the exchange and ensure that all actors receive BIM modeling information in a timely manner and in the required quality. This central BIM manager would need to possess considerable construction knowledge, formal power, great communication skills and needs to be independent of the disciplines involved. The central BIM manager should be the communication hub for the entire project bridging all disciplines involved. Figure 1 illustrates that the BIM manager should be positioned right at the core of the inter-organizational activity. However, in current practice BIM managers are mere "local" managers responsible for bundling the BIM information created within an organization, and managing the input and output of BIM modeling data for the organization in question. Thus, the suggested central BIM manager role represents a significant further development from current practice.

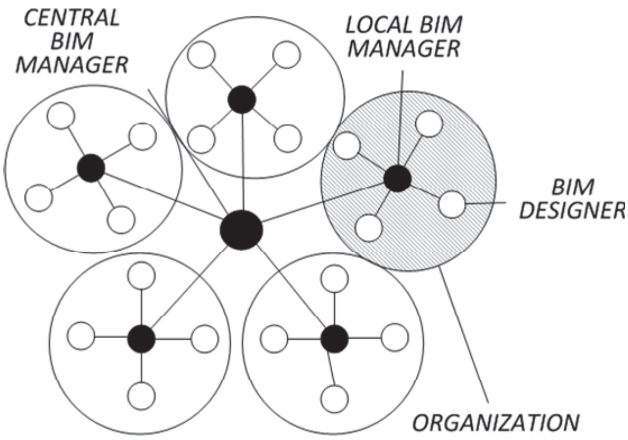

Figure 1: Central BIM manager as communication hub

Last, the dissemination of BIM related knowledge remains a challenge. The focus group practitioners suggested that the establishment of a common forum in which they could get together and discuss challenges related to the use and adoption of BIM, might be useful to overcome this challenge. It has been argued that the establishment of government funded competency centers would be useful to improve BIM related knowledge dissemination in the AEC industry (Hore et al. 2011). Competency centers having a special focus on the needs of the wood-based building industry, addressing both BIM and CNC related topics, could be a useful resource for current practice. However, when organizing the workshop we found that despite a wide interest in BIM related topics, many practitioners were constrained from participating by their busy schedules. Thus, we argue that it may be a challenging task to run regular BIM forums, as practitioners often 'simply' do not have the time to participate in joint discussions on the latest technology.

Due to the wide availability of standard industrial CNC equipment, the wood-based building industry has a great potential to create 'digital fabrication' environments. By digital fabrication environments we refer to processes joining design with construction through the use of BIM and CNC machines (Strass, 2007). However, this opportunity is currently largely left unused, and current practice suffers from the absence of a stable information flow from early design to the code generator. We found several challenges in current practice and suggested possibilities of how to improve communication in project teams.

The suggestions presented for improving communication practices is based on a single focus group discussion with four experts. While these respondents were knowledgeable users of BIM technology, representing different construction disciplines in the wood-based building industry, these findings should be validated through further analysis of industry practice.

6 CONCLUSION AND IMPLICATIONS

Based on a focus group discussion with practitioners in the wood-based building industry, we have identified challenges in the deployment of BIM and CNC technology, and changes that will be required to improve BIM-based design practices among AEC professionals in this industry. Despite heavy investment in the wood-based building industry in BIM and CNC technology, several barriers limit the full use of this, such as low organizational BIM capability, ill-defined exchange processes, and clients not demanding BIM in conjunction with time and budget constraints. To overcome these barriers, the following major changes need to be implemented in the industry: 1) intensify efforts to include 'novel' and 'non' BIM users in collaboration, by offering services where experienced users aid others in creating models; 2) developing guidelines for inter-organizational BIM communication processes in line with the '3D working method', but customized for the information needs of the wood-based building industry; 3) establishing the role of a central BIM manager; and 4) disseminating knowledge on the application of BIM and CNC in wood-based building projects for clients and practitioners alike.

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Article 6

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Succeeding with Building Information Modeling: A Case Study of BIM Diffusion in a Healthcare Construction Project

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Abstract

Technological innovations such as Building Information Modeling (BIM) offer opportunities to improve collaborative work and integration in the architecture, engineering and construction industry. However, research to date has documented how many organizations struggle with how to work based on this new technology, and many implementations fail. In this paper we present a case study of a major healthcare construction project in which the use of BIM was paramount, and where designers claim to have succeeded in integrated design. The designers organized their digital collaboration by establishing 1) change agents; 2) a cloud computing infrastructure; 3) new roles and responsibilities; 4) BIM contracts; 5) an IS learning environment; and 6) by involving software developers. These factors have been identified as influential for the successful diffusion of BIM in this project, and may serve as an example for implementation of BIM in other projects for supporting integrated design.

1. Introduction

Today's major construction projects could not be completed at the necessary speed without the use of advanced Information Systems (IS). Especially, Building Information Modeling (BIM) solutions have proven their value for construction design. BIM is both a new technology and a new way of working providing a common environment for all information defining a building, facility or asset, together with its common parts and activities [29]. Leading architectural and engineering firms use BIM to collaboratively develop virtual 'prototypes' of buildings before they are built [14,19]. When used properly, BIM can aid the architecture, engineering and construction (AEC) industry to become a more innovative sector of the economy [5,6].

Construction designers wanting to use BIM in their project need to develop new processes for their collaborative work [15], and many of today's construction firms hesitate to undertake the necessary organizational changes [24]. Even when firms seek to establish a collaborative environment in their projects, a variety of individual, environmental and technological challenges prove to be difficult to overcome [9,14,30]. Consequently, many firms continue to work in 'siloed' environments instead of encouraging a more collaborative culture. Thus, many of the crucial advantages of collaborative BIM design remain unexplored in wider practice [15].

Recognizing that only a few leading firms collaborate effectively based on BIM technology, recent R&D outlook publications by institutions such as the Council for Research and Innovation in Building and Construction (CIB) argue for the need to further define collaborative processes between the actors in design [7]. This is echoed by literature reviews arguing for the need to strengthen the research on the inter-organizational work surrounding the modeling activity [20,32]. We contribute to this discussion by inquiring into the reasons for why some AEC firms succeed in their collaborative work while others fail. The research question guiding our work is:

How can individual, environmental, managerial and technological challenges be addressed to achieve improved design collaboration through the use of BIM?

The article presents a case study of advanced BIM-based collaboration in a major healthcare construction project in Norway. The desired outcome of the collaborative BIM work was to create "[the] biggest, most complete and best digital model in the world." (BIM manager client)

We present the findings of a series of interviews conducted with the key players in the design team in order to understand how they approached their work. Diffusion of Innovations (DOI) theory [31] serves as a starting point for our analysis of the factors leading to collaboration. The case study approach applied in this study allowed for operationalizing diffusion factors presented in prior work in the empirical setting of a construction project [26], and for building practical and conceptual knowledge about BIM's diffusion as a collaborative system useful for other projects [8].

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2. Theoretical lens

The DOI literature serves as a foundation to understand why and how a set of actors succeeds in ICT adoption and use. An innovation is defined as an "idea[s], practice[s] or object[s] that is [are] perceived as new by an individual or unit of adoption" [31, p. 35]. Researchers interested in how and why an innovation becomes diffused in a social system study "what determines the rate, pattern and extent of diffusion of an innovation across a population of potential adopters?" [31, p. 2]. It has been suggested that the diffusion of an innovation depends on the type and characteristics of the innovation [37], and that traditional DOI theory is best fitted for the study of innovations having an "intra-organizational locus of impact" [18, p. 20]. Nonetheless, DOI has been used to study the diffusion of a wide range of complex, networked technological innovations, including Enterprise Resource Planning systems, corporate web sites, online games, and several more.

BIM and 3D visualization tools in the construction industry can be seen as inter-organizational persuasive digital technologies [27], in that they bring together user experiences by connecting previously unconnected organizations. BIM affords combinatorial innovation by connecting a set of previously unconnected design software modules in a common design space [6, 37].

Traditional DOI theory views innovation diffusion as a linear process and the DOI contagion model assumes that "innovations are being spread but are not changing" [37, p. 1403]. However, combinatorial innovations such as BIM mutate and evolve while they are spread [37]. To understand the dynamics of such innovations researchers need to go beyond what has been suggested in traditional DOI literature and inquire into the "local, complex, networked, and learning intensive features of technology, [and] the critical role of market making and institutional structures in shaping the diffusion arena" [18, p. 14]. Moreover, to provide a 'faithful' account on the diffusion of BIM it is important to acknowledge its evolutionary component and "trade simplicity and generalizability against accuracy" [18, p. 14].

How readily an innovation is diffused in a social system depends, among others, on the 'voluntariness' of the innovation decision. Literature suggests that three different types of innovation decisions exist [31]:

- *Optional* – a decision made by an individual who is in some way distinguished from others in a social system.
- *Authority* - a decision made for the entire social system by few individuals in positions of influence or power.
- *Collective* – a decision made collectively by all individuals of a social system.

Researchers have found that construction projects make a challenging 'diffusion arena' for networked technology such as BIM [26]. Several reasons are mentioned for this: first, construction firms exist along a spectrum ranging from highly computer literate 'diffusion ready' organizations to those hardly using computers in their work [25,34]; second, AEC organizations struggle to develop new forms of organizing and to change their established ways of working [12]; third, AEC firms frequently fail to establish common infrastructures for BIM technology use within and between organizations [2]; and last, many construction executives remain skeptical about the business value offered by BIM technology for their projects [35].

The practical side of BIM diffusion and use is at the focus of several studies. Some scholars apply a DOI approach to explain intra-organizational BIM diffusion [26,27,28,36], or the industry wide diffusion of BIM [25]. Much of this prior DOI-based research relied on surveys to identify generalizable factors important for BIM diffusion [26,27,36]. Researchers studying behavior of various organizations in BIM adoption have used theoretical lenses such as Actor Network Theory [16] or Boundary Object Theory [23] to develop their findings. This work established for instance that the creation of networks between a set of AEC organizations frequently fails.

We argue that prior work can be extended by providing a more in depth account on the necessary conditions for BIM use at the inter-organizational level [18]. In our study we use a set of diffusion factors identified by Peansupap and Walker [27] as a starting point to structure our analysis:

- *Individual factors,* refer to the personal characteristics of an individual working with the technology, such as IT skills, capability to learn, and previous experience of IT.
- *Environmental factors,* describe the workplace environment in which the individual works, such as the availability of an open discussion environment and the possibility to share knowledge about ICT.
- *Management factors,* focus on the managerial approaches taken to organize the digital work, and the availability of ICT support considered important for ICT diffusion.
- *Technological factors,* technology characteristics, e.g. functionality, speed and accessibility, which may influence the diffusion of an innovation in construction projects.

Based on these factors we present how the design team in our case study established a collaborative BIM work space for their project.

3. Method

We conducted a case study of a major hospital construction project in Moss, Norway, initiated by the Southern and Eastern Norway Regional Health Authority (Helse Sør-Øst). A case study approach is appropriate to understand ‘sticky’ practice based problems where experiences and the context of the action are important [4]. The project was suggested to us by the educational coordinator of the Norwegian branch of the industry-led organization Building-SMART©, as an example of advanced BIM-based design practice. The project comprises the construction of several facilities including buildings for emergency, surgery and intensive care, patient rooms, psychiatric care, and for services such as a laundry and central sterilization. Altogether, the buildings comprise a gross floor area (GFA) of 85.082 square meters, and the project costs are estimated at € 670 million. In hospital design architects, health-care experts and users need to work in a “dynamic alliance” in order to build a hospital satisfying future users [1]. The Health Authority decided to use BIM technology to facilitate communication and teamwork among the parties involved in design. The outcome of the collaborative design process was a highly detailed virtual model signifying each of the buildings’ components ranging from sprinkler heads to lighting fixtures. Thus, this project in which BIM and collaborative design was prioritized makes a compelling context for our study.

The drawings were prepared by 100 architectural consultants working for three different firms, and roughly 100 engineering consultants covering different areas of expertise. These consultants had different levels of BIM maturity. Only a few consultants had experience from jointly creating semantically rich BIM based models (5-10%), some had experience from creating disciplinary models (15-30%), while most of the consultants had never used modeling technology except for creating simple 3D visualizations (60-80%). Percentages above stem from an “educated guess” by two interviewees (client#1 and architect#1).

Our data was collected through eight semi-structured interviews with design professionals, aiming to gain an understanding of the phenomenon by asking those experiencing it. The target was to interview BIM knowledgeable key actors in the design team. All interviewees were disciplinary or project level leaders responsible for BIM-based design and management. The interviews were conducted in April 2013, at a point in time when the design had been ongoing for three years and the team worked on finalizing the detailed design. Table 1 provides an overview of the interviews conducted. Six interviews took place at the designers’ construction site offices in Moss, one was conducted via Skype and one took place at a firm’s branch office in a different part of Norway. All interviews were voice recorded, transcribed, and coded by using the qualitative data analysis software NVivo9 [22]. Categories were derived from the data by assigning nodes to notions which could be related to the topics as presented by Peansupap and Walker [27].

Table 1. Interviews conducted

Affiliation	Project level	BIM services provided	Interview Duration	Interview technique
Client #1	Project	BIM manager (strategy)	60 min	Face-to face
Client #2	Project	BIM manager (technical)	60 min	Face-to face
Architect #1	Discipline	BIM coordinator (architectural)	45 min	Face-to face
Architect #2	Discipline	Façade designer	20 min	Face-to face
Electrical Engineer #1	Discipline	BIM coordinator (electrical engineering)	60 min	Face-to face
Electrical Engineer #2	Multi-Discipline	BIM coordinator (all engineers)	75 min	Face-to face
HVAC Engineer	Discipline	BIM coordinator (HVAC engineering)	35 min	Face-to face
Structural Engineer	Multi-Discipline	BIM coordinator (all engineers)	190 min	Skype

4. Analysis

The analysis part of this paper is structured as follows: first the type of innovation decision is presented, followed by a systematic presentation of the diffusion factors as suggested by Peansupap and Walker [27]: 1) individual; 2) environmental; 3) managerial; and 4) technical. The factors discussed have been identified based on interview statements that could be related to the diffusion of BIM.

4.1 Innovation decision

The decision to prioritize collaborative BIM use for the hospital’s design was made by the client’s organization, on behalf of the project team. Like in most construction projects, the client held a position of influence and power in this project. Thus, following Roger’s typology for innovation decisions, the decision to use BIM in this project can be seen as an “authority innovation decision”, with the client as central actor in the diffusion system [31]. A drawback of authority driven innovation decisions is that new practices might be resisted by other members of the social system (e.g. architects, engineers). To minimize the risk for this, the client formulated contracts in which the collaborative use of BIM was explicitly demanded from all parties wishing to partake in the design of the buildings. BIM technology was considered important:

Well, as a building owner it is an important part of the strategy to have building models which can be used [...] and the intention is to save money in the operation phase. (Client, BIM manager 1)

The complexity inherent in large healthcare construction projects provides an "opportunity to harness the strengths of BIM" [19, p. 446]. The client anticipated that a semantically rich and highly detailed BIM model would be a useful resource for decision making, facilities management, and for active inclusion of the users in the facilities design (doctors, nurses).

To insure that the outcome of the model-based design would be of sufficient detail for facilities management, the client made clear that the model was to be an: "acceptable [virtual] prototype of the building". However, only few leading AEC organizations possess a sufficient level of expertise to collaboratively create models of such high quality. In awareness of this lack of expertise, the client promoted BIM competency development as a project goal:

The client has the objective to implement model-based design in this project and shall contribute to increase the competence about BIM in general and insure the knowledge gained can be transferred to other projects. (Client, BIM manager 1)

Introducing new technology is a costly undertaking and additional funding was needed to insure the design team could learn model-based collaboration while designing the project. Additional funding was made available by the client in conjunction with the Norwegian government. To guide the project's design team towards the anticipated goal of creating a sophisticated building model, the client appointed 'opinion leaders' or 'change agents' enforcing the collaborative use of modeling technology at project level. Two BIM specialists having the power to promote BIM use in the project were appointed by the client. One of these BIM professionals had the responsibility to manage the strategic aspects of the BIM collaboration whereas the other had the task to manage technical aspects of the BIM-based collaboration. However, the client decided to procure the project based on a design-bid-build method. This traditional procurement method involves three sequential phases: design, tendering, and construction. A drawback of procuring the project this way is that contractors creating the workshop design joined the project relatively late and thus were largely excluded from collaborative BIM-based design.

4.2 Individual diffusion factors

The use of BIM to facilitate the collaborative design work in this project was not a matter of choice for the design team. The client simply imposed a new way of working and collaborating upon the design team. This decision was not without risk, as collaborative BIM-based design is significantly different from the traditional way of working in this industry. The designers might have responded with hesitation or even resistance to the technology and the new way of working. The client marketed the project as a "BIM learning project", allowing companies to develop skills and processes while working on the project. This created a positive attitude towards the new technology and the new collaborative way of working. As noted by one designer, who initially had only rudimentary BIM skills, the team enjoyed having had the opportunity to learn how to work based on BIM:

What I have learned [about BIM]? Everything. When I came here my BIM skills had never been good, I kind of self-trained me. [...] Now, I have learned everything about BIM [and] I advise everybody to do this kind of project. (Electrical engineer, BIM coordinator 1)

Other, more experienced designers saw this project as a good opportunity to advance their firm's BIM development. The electrical engineer stated:

Those projects provide a good opportunity to take the next step [in BIM] because you have a big project and professional builders and owners. [...] I am sure that we will use many of the things we learned here in all our projects in the years to come. (Electrical engineer, BIM coordinator 2)

Ergo, some firms used this project to develop templates for new processes, advance their knowledge about available technology, and to develop BIM solutions. These designers built transferrable knowledge which could be 'rolled out' in other projects.

The design team had an overall positive attitude towards collaborative BIM design and the structural engineer stated that BIM helped to get rid of some "tiresome, time consuming and dull work" included in traditional design. In addition, there seems to be wide agreement that BIM has positive implications for design quality and the overall quality of the building. However, having to purchase systems useful to work faster and more efficient can lead to a contradicting situation for some of the designers:

We get paid by the hour so if we buy software to save time it is the client that benefits from it. Because we have to use our money to buy the software and we get less money from the client. But the client will benefit from us using less time. (Structural engineer, BIM coordinator)

4.3 Environmental diffusion factors

Establishing a collaborative work environment requires creating structures, rules and practices that promote cooperation. The establishment of a work environment depends to some extent on prior experiences: "in every project we [the designers] stand on the shoulders of the previous projects" (structural engineer, BIM coordinator). The design team in this case project arranged their collaborative environment for BIM-based work by establishing: 1) guidelines and rules for model based work; 2) roles and responsibilities; 3) a project BIM-room; and 4) cross-disciplinary exchange and control processes.

1) Guidelines and rules. The design team developed a project 'BIM manual' based on a template for BIM use provided by Norway's largest construction client [28]. The architect suggests that BIM manuals and handbooks are of crucial importance and should be established before the design work commences:

The key learning is to be a little in front of planning to create some rules for how we work, how we draw and who is doing what, and that you have to make a BIM manual before you start. (Architect, BIM coordinator)

Furthermore, the designers customized the manual for the particular needs of a hospital building project. The manual specified the way in which modeling information was to be delivered by the parties in the project. The manual included for instance a naming convention for parametric objects allowing designers to tag every component used in design in a consistent way based on unique identifiers specifying the location and type of component. In addition, the manual specified the file exchange format, in this case Industry Foundation Classes (IFC), to provide a basis for reliable cross-disciplinary information exchange. Beyond the project level manual, each design discipline developed a BIM handbook which provided the individual designers working hands on with the modeling technology with some practical advice of how to create models that would comply with the project level agreements specified in the BIM manual.

2) Roles and responsibilities. The design team created the position of "disciplinary BIM manager". These managers had the responsibility to monitor the modeling activity within disciplinary design groups. The structural engineer described the tasks involved in being a BIM manager as to include quality control of disciplinary models and to insure their compliance with the project's BIM manual. Further tasks are the preparation and weekly submission of disciplinary IFC models for the cross-disciplinary model control. The coordinators engaged actively in disseminating knowledge about the BIM manual and its practical implications for the designers. Disciplinary BIM coordinators had to report to the client's project level BIM managers whose job included the following tasks:

Well, [the job of a client's BIM manager] is to secure that the BIM model is working as it should and that it is suited for the operation phase after the building is finished. Working with that is quite important. So we put together the different sections of the building [into one model of] the whole building. (Client, BIM manager 2)

The client's BIM managers assembled the models produced within the disciplines on a weekly basis into a joint model of the entire building. This work included to combine 42 different IFC based models created within the disciplines. The complete model was then used for clash detection in order to find and eliminate inconsistencies between the designs created within the different disciplines.

3) Project BIM room. The design team agreed that it would be necessary to establish a project BIM room as a central location for the weekly (Monday) cross-disciplinary meetings in which the designers discussed the overall building model assembled by the client's BIM manager. The room was equipped with two screens and a computer to which the updated and combined model of all disciplines was uploaded. Not only was the room intended as a collaborative space for the designers, but also for the contractors so that they would be able to look at the models while constructing the building. Figure 1 shows the project's BIM room.

Figure 1. BIM room at hospital construction site

4) Cross disciplinary exchange and control process. The design team developed a process for cross-disciplinary model control. The weekly routine established for design exchange and model control included the following activities:

Thursday - All designers make their models ready for exchange and deliver these to their disciplinary BIM coordinators. The coordinators control the model for correctness and create exchangeable IFC files that are uploaded via a web-server (Byggeweb©).

Friday - During the night from Thursday to Friday the delivered IFC files are synchronized with the local construction site server. Friday morning the client's BIM manager has access to all disciplinary IFC files via the local server. Next, he controls all models for compliance with the BIM manual and for logical errors. In case of obvious errors he requests new IFC models. Last, he assembles all disciplinary sub models into a joint model of the entire building by using the model checker software Solibri©.

Monday - The client's BIM manager uploads the model of the entire building to the computer in the BIM room. Then, in a cross-disciplinary model control meeting with the entire design team the models are controlled for geometrical clashes based on a set of pre-defined clash-detection rules for Solibri©. Further, the designers conduct virtual walk-throughs in order to detect other necessary improvements. All design tasks are protocolled, tagged and extracted from the digital Solibri© model. Last, the disciplines receive lists with design tasks requiring immediate attention.

Tuesday-Thursday - The client's BIM manager controls the design changes undertaken based on the agreed task lists and in case of compliance approves the respective part of the model as ready to be built. After approval, the model is used to extract data to plan areas, rooms, functions and the time schedule based on database applications (e.g. dRofus©; Navisworks©).

According to the designers the cross-disciplinary model control procedure had both advantages and disadvantages. The advantages include that more design errors could be identified before the construction commenced. In addition, the increased design clarity allowed designers to develop a better understanding of each other's work, creating a better, more respectful relationship between the designers:

Suddenly, the structural engineer understands why the architect is doing what he is doing. […] You get a totally different understanding for each other's challenges. (Structural engineer, BIM coordinator)

On the downside, increasing clarity in design increased the accountability for the designers. This accountability may be unwanted in cases where the design is still under development. To provide an example:

One corner of the hospital may be very well developed and almost finished and another part of the project can be on a preliminary stage. So, then when the client gets the model of the whole hospital he finds things that clash in the unfinished areas because that is really not coordinated yet. (Structural engineer, BIM coordinator)

4.4 Managerial diffusion factors

The seemingly most prominent managerial challenge related to BIM work in this project was that most designers did not have any prior experience in BIM design and collaboration. In a typical construction project this issue would have been more challenging to resolve. In our case study additional funds granted by the Norwegian government were available to develop BIM knowledge. This makes the study a showcase of what can be achieved once enough funding is available:

For 60-80% of the people that have been working in this project, working and drawing in a BIM project model was totally new […]. They [the client] have got some incentive from the Norwegian state […] so we have extra hours to train our people. (Architect, BIM coordinator)

The design team decided to use various approaches to IS training, and they decided that most of the training should take place on the construction site to keep the disruption of the daily design work at a minimum. The training was delivered based on four basic approaches: 1) super users (internal and external); 2) cross-disciplinary BIM training; 3) disciplinary BIM training; and 4) learning aids.

1) Super users - highly capable and BIM experienced designers were identified and formally appointed as 'BIM super users' for their disciplinary design group. These super users were seen as a 'BIM task force' to start up the project and provide training and help for less experienced designers. These persons had a double role of troubleshooting practical BIM problems and training their peers in BIM use, in addition to working in their usual roles as project engineers or architects. Due to the lack of availability some firms had to appoint external super users to train their designers, e.g. the electrical engineers hired an expert from a software vendor to train their people in BIM design until they felt confident to work without this help.

2) Cross-disciplinary BIM training - three hour courses were developed to introduce all designers to the basic functionality of the cross-disciplinary systems used at project level including Solibri© for clash detection and Navisworks© for time scheduling. These courses were designed to provide a strategic overview rather than to teach the actual hands-on work with those systems. The courses were held on the construction site.

3) Disciplinary BIM training - these training programs were designed to teach users the hands on skills required to design based on a particular disciplinary BIM design system (such as Revit©MEP or Revit©Architecture). These courses were targeted foremost at those designers that needed to learn from 'scratch' how to design based on BIM. The training was organized by software vendors and usually went on for several weeks. Typically these courses were held at a vendor's training facilities.

4) Learning aids - were developed by people having extensive prior experience from working hands on with BIM technology within their disciplines. The learning material was customized for each discipline's unique learning needs. The material was bundled into a set of disciplinary BIM handbooks placed at every BIM workstation in the project. These manuals provided hands-on knowledge on BIM design and included step by step recipes which could be followed by the designers in order to create a digital model.

Adopting new systems and training the workforce to use them is a costly undertaking, and its success depends largely on the degree of top-level support in each of the firms participating in design.

You cannot do anything without top-level support. […] We roll out [new technology] wherever we have a budget for it and where it is cleared by the [top] management. (Structural engineer, BIM coordinator)

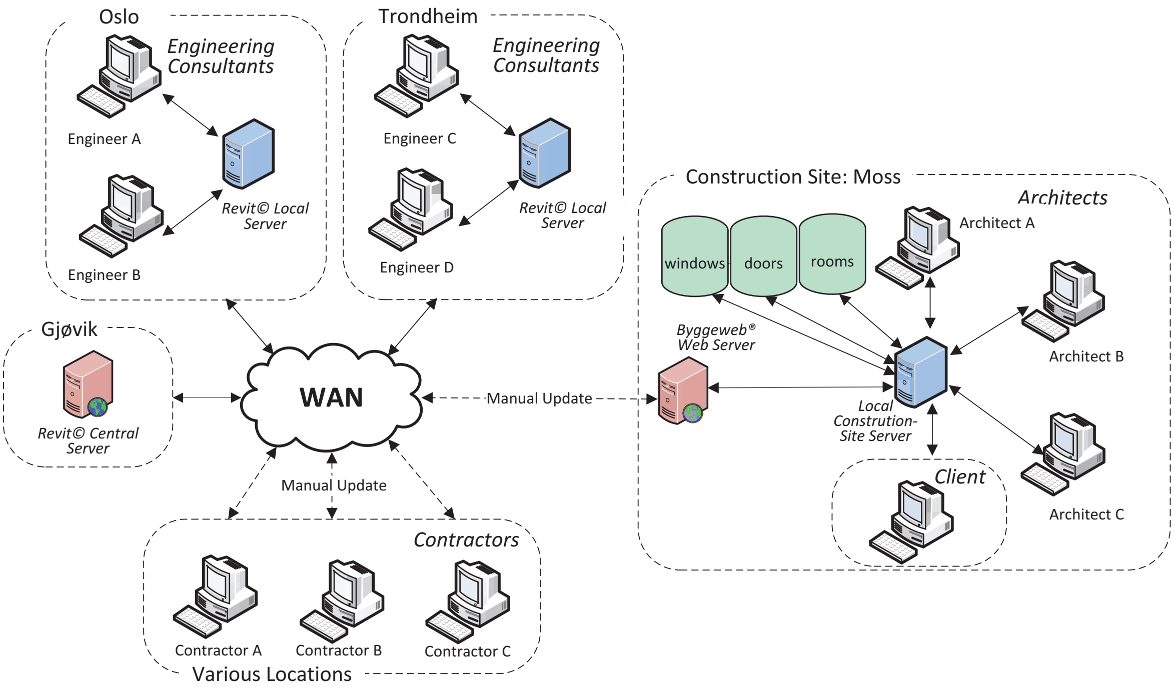

Figure 2. Network for collaborative BIM design

4.5 Technological diffusion factors

Collaborative BIM design requires a set of BIM workstations to be linked by a supportive server infrastructure. At project initiation the design team decided that all designers should work physically co-located at the construction site in Moss. Co-locating the design team was regarded as useful to build team relationships and to improve communication in design. Thus, all BIM workstations were initially set up on-site and linked towards a local server. The server functioned as a team work space in which the central BIM model was placed and the designers worked 'live' on the same model. This co-located setting and infrastructure was used throughout the conceptual design phase. When the design advanced to the detailed design phase the infrastructure was altered:

In the beginning we were all sitting here working towards a local server. When the project advanced further in detailing we needed more people and all these people could not travel to this place because they were all located in different offices. (Electrical engineer, BIM coordinator 2)

There was a need to include additional design team members distributed geographically (Oslo, Trondheim etc.). The designers agreed that the cost of supporting a fully co-located team and the expenses of travel involved would outweigh its benefits and justify a more distributed setup. In this second phase the design team set up a 'mirror' web-server (Byggeweb©) featuring the same content as the local server. This web-server allowed for distributed work where all designs could be accessed and altered via the internet.

In addition, the engineering consultants decided to build a server infrastructure based on Revit © server technology. This allowed them to work in a real time 'live' modeling collaboration while operating in a distributed setting. They placed a Revit©CentralServer in Gjøvik and linked all their design offices through the use of Wide Area Network (WAN) technology to this server. Thus, their distributed BIM workplaces were linked and models were synchronized every night. In essence this meant that designers in Trondheim would be able to see the design changes a colleague in Oslo had produced. The setup of the collaborative infrastructure during the detailed design phase is depicted in Figure 2. Figure 2 shows that the design team has in essence built a 'cloud computing' infrastructure for their BIM project. Building such an infrastructure is however often only feasible for large projects:

You are able to do that in bigger projects because you get time to develop it […] but often in small little office building projects, like here in Kristiansand, you have maybe half a year to finalize the design of the building. (Electrical engineer, BIM coordinator 1)

After having set up the collaborative infrastructure the design commenced. Since none of the designers had prior experience in creating a digital model for such a large facility, the design team was surprised by the sheer amount of data that was to be shared through this network. The models quickly became far too large to be handled by the designers' computing equipment:

> That was a wakeup call for us in the beginning that we actually cannot use those crappy computers anymore, we need top of the line computers because it is so much data. (HVAC, BIM coordinator)

To establish a stable information flow between all design and database applications used in the project network these applications needed to be interoperable. The design team approached this challenge by firstly establishing that all design software used was to be IFC compatible. Second, all designers not yet working based on BIM software adopted software solutions similar to those already used in their design group. For example, two architectural firms adopted 'Revit© architecture' since a third firm already worked based on that software. Revit© software was used by most engineers and by the architects allowing them to collaborate 'live' based on the work sharing functionality embedded within Revit. Having most designers work based on software by the same vendor eliminated most interoperability challenges.

In addition, all the software for the door, window and room databases and the servers needed to be aligned and linked to allow for synchronization of the digital works. To arrange for this an external ICT consultancy was appointed to set up and service the infrastructure. The designers faced challenges where the software in itself was not sufficient for its purpose. For instance, the application used to design the sprinkler system proved to be unfit for large structures, or the system used in clash detection proved to be insufficient for clash detections of large models. The structural engineer stated that these challenges were addressed by appointing a software consultancy:

> We do have [a software company] that on our request developed a software to be used in Revit so the fire engineers and the acoustic engineers can take a copy of the architect's file and put the fire ratings on the doors and walls. (Structural engineer, BIM coordinator)

Appointing the developers helped to address some of the problems experienced, for instance, the fire protection engineers could partake in BIM design. As a result of the efforts undertaken to establish a functional BIM collaboration, the design team collected large amounts of documentation data on the individual components used in the facilities design and placed this in databases. However, so far the client has not been able to identify any commercially available system useful to structure the data in a meaningful way for facilities management.

5. Discussion

The case project is an example of advanced practice where a collaborative BIM work environment has been established. The established design space linked architects, engineers and clients. However, the link between the design team and the construction firms was less well developed and contractors were largely excluded from the collaborative work. This resonates with earlier research arguing that those working in 'the periphery of digital innovation networks' are frequently excluded from innovative practices [38]. Further, even though the design team claimed to have succeeded in BIM design it remains to be seen whether the project as such will be regarded a success after completion.

Keeping these limitations in mind, we argue that our study provides a useful starting point for practitioners seeking to set up a collaborative BIM workspace in their projects. The key diffusion factors aiding the case project's designers to establish their collaborative work environment are summarized in Table 2. These factors, however, need to be seen as a product of their context, and practitioners would need to evaluate their fit to other project situations [18]. For instance, the case project has been unique in that BIM-based work was supported by a grant provided by the Norwegian government. Even though the diffusion factors would need to be customized to a specific construction context some of the approaches have proven effective to eliminate some widely experienced problems in construction projects:

First, establishing a BIM learning environment helped to equip all designers with the capabilities and maturities required for collaborative BIM work. Extant research has identified the uneven distribution of capabilities and maturities in project teams as a major barrier for collaborative design [34].

Second, involving system developers during the design to assist designers in overcoming technical challenges proved effective to connect previously unconnected designers (e.g. fire protection engineers).

Third, establishing a cloud based infrastructure allowed the designers to choose either to work co-located or distributed. The opportunities of cloud computing and virtual teams for BIM-based design are discussed in the literature, and it is debated whether co-located or virtual design teams perform better in BIM-based design [11,13]. We argue that the value of virtual teams and cloud computing technology for construction is an area in need for further research.

Fourth, there is a wide debate in current BIM research about the challenges of technical interoperability among different BIM design solutions [10]. The case design team addressed this challenge by deciding to work, where possible, based on software provided by the same vendor. In addition, they agreed to only use applications supporting the IFC open file exchange standard. However, just adopting new

Table 2. BIM diffusion in the case project

DOI Element	Case project's key diffusion factors
Decision	- Authority innovation decision by the client - BIM integral part in contractual arrangements - Government funding to increase industry's BIM competency
Individual	- BIM use promoted as project goal - Change agents appointed at project level to enforce BIM use - Project framed as a BIM learning project - Possibility for designers to develop BIM competence in the project
Environment	- Formulation of guidelines and rules for collaborative BIM work - New roles and responsibilities developed - Project BIM room - Cross-disciplinary model exchange and control process
Management	- Organized approach to IS learning (super-users, cross-disciplinary and disciplinary BIM training, and learning aids) - Top management support
Technology (hardware)	- 'Cloud computing' network for distributed and co-located design - Top of the line equipment
Technology (software)	- Interoperability achieved by using software from a single provider - All software used IFC compatible - Close collaboration with software developers to improve the functional affordance of BIM technology

systems may not be a feasible solution for projects where limited funds for BIM-based work are available.

Last, the design team created a holistic approach to manage their collaborative design by establishing formal arrangements (contracts), a coherent way to produce models (BIM manual), a model exchange process, and defining roles and responsibilities for their collaboration. Former research has suggested that establishing an overall 'organizing vision' is essential for the functionality of inter-organizational systems [17,21], and this case shows how that could be achieved in construction projects.

It would be an interesting avenue for further research to inquire how such shared organizing visions for working together in BIM could be established in other project situations. Our case study showed that some issues for collaborative design remain unsolved, such as the lack of commercially available applications to reuse BIM data for facilities management. This finding does not come as a surprise, as researchers are just beginning to explore BIM's application areas for facilities management [3].

Our study has documented that if designers are given sufficient financial resources it is possible to achieve integrated design in construction projects, and has provided insights for practitioners seeking to diffuse BIM technology in their projects. In addition, the usefulness of DOI as a theoretical lens to study BIM-based collaboration in a construction project has been shown. However, we developed our view on BIM diffusion based on a single case study, and further studies should be conducted in other types of projects to validate our findings.

6. Conclusion

This paper has presented a case study of a construction project in which the design team succeeded in integrated design based on digital modeling technology. By doing so the team managed to reduce some of the tiresome and time consuming work in construction design, and, according to the client, to produce an acceptable virtual prototype of the buildings.

By conducting a study based on DOI we were able to identify inter-organizational factors driving the diffusion of BIM technology at the project level. We identified how individual, managerial, environmental, and technological challenges typically experienced by construction firms in BIM diffusion can be addressed to set up a collaborative BIM workspace.

The identified diffusion factors include the establishment of BIM 'change agents', putting in place a cloud computing infrastructure, appointing software developers, establishing solid BIM contracts, a systematic approach to IS learning, and the establishment of new roles and responsibilities.

However, even though we claim to have provided a faithful account of the factors that aided designers in this case study to facilitate their collaborative work, these factors need to be seen as a product of their context. Practitioners seeking to find a diffusion approach for their projects need to evaluate whether these factors fit their given project situation.

We argue that BIM technology and its use in the AEC industry is an interesting field in need for further IS research, including questions such as: what is the value of virtual teams and cloud computing technology for construction projects? How is the diffusion of BIM influenced by a construction project's context? And how can the content produced in BIM design be managed in order to be useful for facilities management?

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