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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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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].

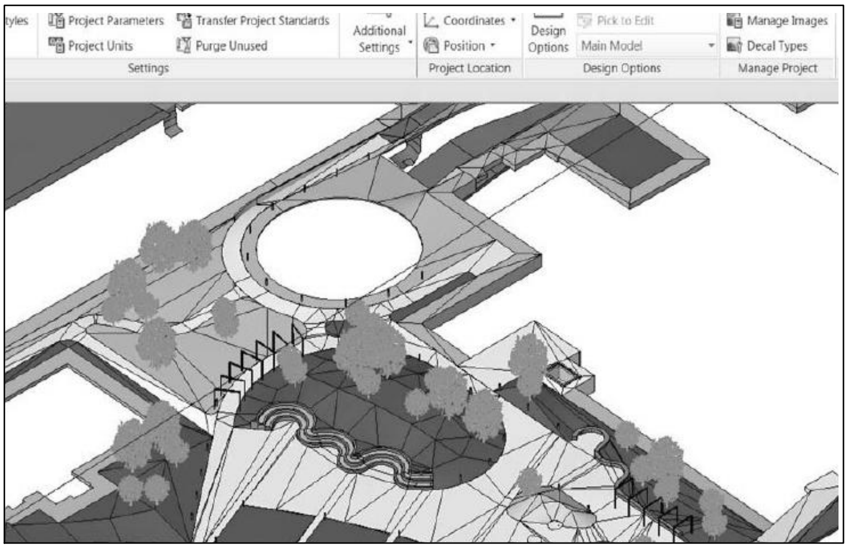
The next section introduces the BIM concept and the construction informatics research field, including the framework guiding the research review. Section III presents the methodology applied for the literature review. The findings from the review are presented in Section IV, and the implications for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

II. INTRODUCING THE RESEARCH DOMAIN

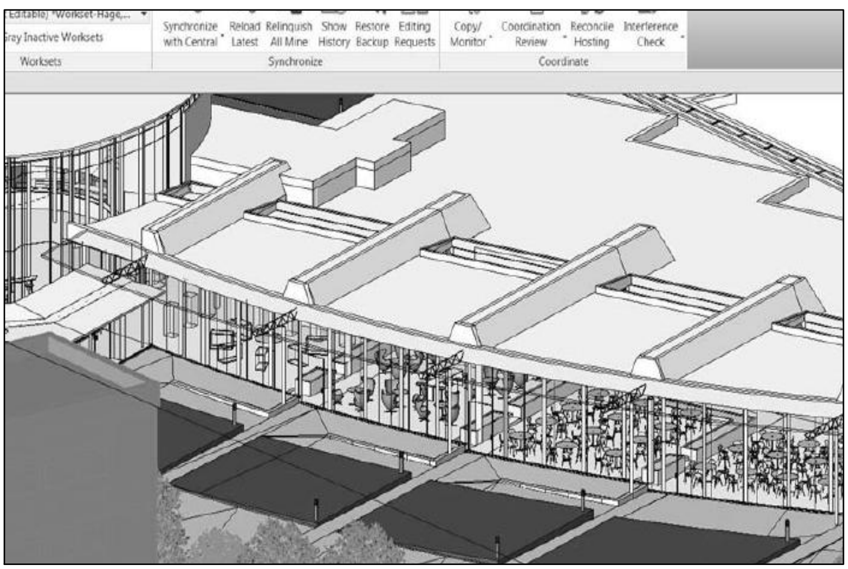
Building Information Modeling: From 2D to 3D Based Construction

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.



a) Landscape architecture model view



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.

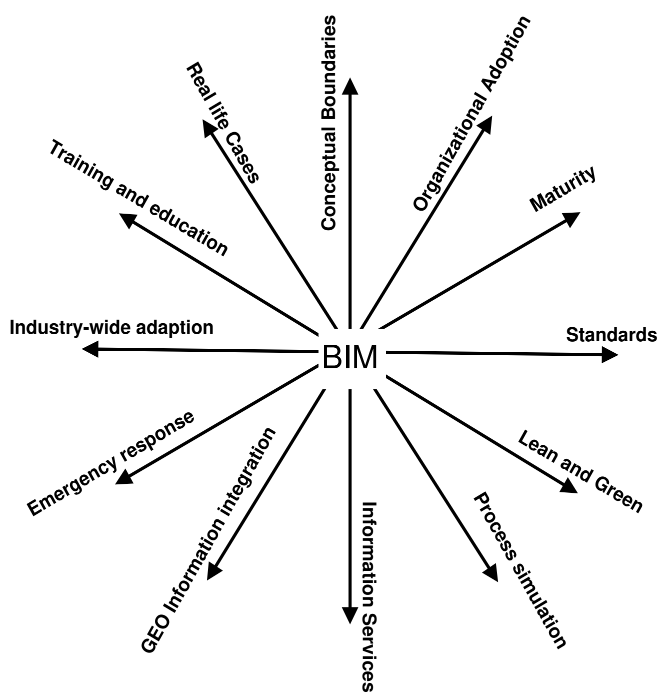


Figure 2. BIM Research Compass (Adapted from Isikdag and Underwood, 2010a)

- *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.

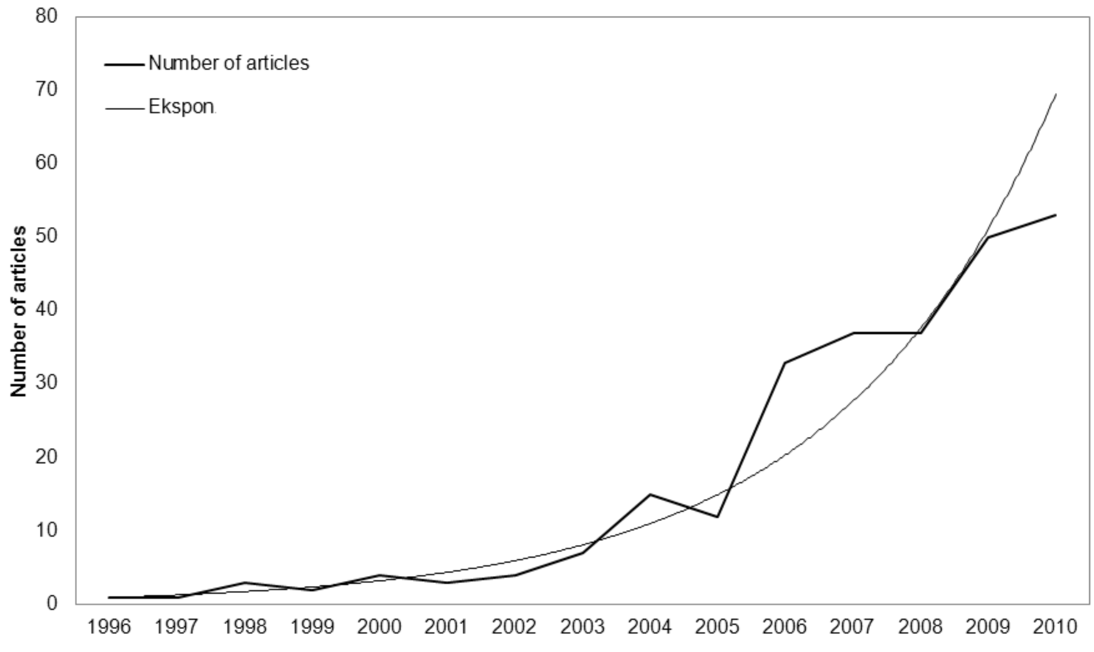


Figure 3. Article Output per Year in the Area of BIM, VDC, and 3D Modeling

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.

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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1. These links existed as of the date of publication but are not guaranteed to be working thereafter.
2. The contents of Web pages may change over time. Where version information is provided in the References, different versions may not contain the information or the conclusions referenced.
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