BIM ADOPTION IN INTEGRATED SUPPLY CHAINS: A MULTIPLE CASE STUDY

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This paper explored the status of BIM adoption in construction Supply Chains (SC). The benefits of BIM are found from design management, to virtual construction and site management. The study is structured upon the assumption that BIM not only supports intra-firm collaboration, but also improves inter-firm collaboration in projects with SC management (SCM) application. Next, a set of real-world SCM projects was analysed empirically via interviews and questionnaires. These BIM-based SCM projects displayed various degrees of SC team integration and BIM collaboration routines. The multi-case analysis suggested that BIM-readiness was a significant parameter for choosing partners and forming the SC partnership. Finally, the paper compared various levels of BIM collaboration to SC maturity and discussed the benefits and lessons learned from combining BIM technology and SCM theory.

Keywords: building information modelling (BIM), supply chain management (SCM), BIM-based collaboration, integration.

INTRODUCTION

The use of Building Information Modelling (BIM) becomes the norm in Architecture, Engineering and Construction (AEC). Numerous different professionals apply BIM in different phases. Undoubtedly, BIM offers many benefits in AEC projects, such as time reduction, communication and coordination improvement, lower costs and fewer returns for information (Azhar, 2012, Bryde *et al*., 2013). Yet, there is an abundant rhetoric on BIM's collaboration benefits (Barlish and Sullivan, 2012, Mondrup *et al*., 2012), but without examining the impact of BIM in already integrated multi-disciplinary teams above organisational barriers, e.g. Supply Chain (SC) partnerships.

Supply Chain Management (SCM) manages the flows of material, information, and cash, by encouraging close project-based collaboration and engagement to future collaborations within strategic partnerships. This close relation among different professionals implies sharing both rewards (e.g. fewer economic uncertainties) and risks (Vrijhoef, 2011, Vrijhoef and Koskela, 2000). On one hand, SCM underperforms when it merely adopts the traditional workflows, due to lack or redundancy of information. On the other hand, BIM offers an integrative technology for information sharing among extended teams. However, the changes from BIM-enabled SCM and the exact BIM-enabled collaboration process are not yet adequately researched.

The combination of BIM technology and SCM practices is understudied. There is significant research on BIM collaboration for extended project-based teams (Cidik *et*

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al., 2010, Van Berlo *et al*., 2012), but not for already structured, trusting and long-term SC partnerships. This paper describes BIM use within such SC partnerships. It reveals the changes in the SC team roles and investigates the practical issues of BIM use in its full potential (multi-stakeholder use) within the SC. This study reports on BIM adoption in five real-world SCM projects by analysing the engagement to BIM and SCM and concludes that nowadays a BIM-enabled routine can greatly promote SCM. Likewise, BIM collaboration process is greatly enriched by SCM practices.

This paper performed a multiple case study research to analyse the changes induced in SCM settings by BIM adoption and to describe the actual BIM use within such multi-disciplinary teams. The rest of the paper contains the background and presents the methodological framework. Subsequently, the paper presents the findings and with the discussion section, it concludes with the status quo of BIM use in SC partnerships and a set of suggestions for effective BIM-enabled SCM application.

RESEARCH BACKGROUND AND GAP

The recent research on BIM adoption in AEC suggests that project complexity raises from the involvement of an increased number of interacting project actors (Hickethier *et al*., 2013, Zavadskas *et al*., 2010). Moreover, a recurring issue in the literature has been the need to inspire and retain trust during the multi-disciplinary collaboration with BIM (Cao *et al*., 2015, Miettinen and Paavola, 2014). Yet, in practice, the distributed relations among the SC actors that are engaged in SCM practices already present trust and openness. By consciously aligning a firm's operations to that of a federation of SC partners, the relations transform from distrustful to transparent. Thus, SCM offers a fertile ground for trust in BIM-based collaboration.

SCM regulates the material, information and cash flows among a set of aligned companies. Previous research has underlined that BIM is fully capable of supporting these flows. One, BIM regulates the material flows through BIM-based monitoring methods (Irizarry *et al*., 2013). Two, BIM has positively changed the cost estimating processes by providing ground for reliable estimations (Forgues *et al*., 2012, Hartmann *et al*., 2012). Three, BIM effectively manages the information flows, since it is a structured data model of building information per se. Thus, BIM supports SCM by offering a set of options for managing the material and cash SC flows and various methods for the rationalisation and standardisation of the information flow.

As described above, it is evident that BIM technology and SCM theory can mutually support one another when they are simultaneously applied in projects. After all, the SC partner selection process has transformed from price-based criteria to more soft criteria, such as quality of collaboration (Pala *et al*., 2014, Sporrong and Kadefors, 2014) or their ability to use ICT, e.g. BIM, as an interface (Mahamadu *et al*., 2014, Yin *et al*., 2014). Thus, we hypothesise that BIM transforms the roles and SC partner relations in SCM. Also, practical issues have emerged during BIM adoption in multi-disciplinary teams (Van Berlo *et al*., 2012, Cidik *et al*., 2010), which suggests that BIM research takes the distributed character of SCM, under consideration.

In the traditional SC research the general contractor, who has been usually considered the *"focal"* firm, together with sub-contractors and often some suppliers form the SC. Today, many more different specialties are actively involved in the SC partnership and the theory of *"focal"* firms has shifted towards a more distributed and complex system. BIM requires the active involvement of various other professionals, (apart from the traditional SC) such as clients, asset owners and design firms (Love *et al*., 2014, Son *et al*., 2015). This paper addressed organisational and collaboration aspects of BIM by exploring and proposing SCM as a solution. It explored two main research questions and filled the respective gaps with empirical data:

1-What are the changes in the roles of the SC actors from BIM-enabled SCM?
2-How is BIM-based collaboration currently applied within SCM practices?

METHODOLOGY

The research is based on a case study research design. The case studies were selected for exploring the combination of SCM theory and BIM in practice by providing a *"real-life context"* to the hypothesis (Yin, 2003). To offer a pragmatic overview, the case results were later compared to the literature, to strengthen the existing research or detect any discrepancies. To ensure the reliability and generalisation of the study, strategies for a diverse sample of representative BIM-based SCM projects were used.

The case study included a sample of representative projects, selected from a set of email communications carried out during the last quarter of 2014 towards 52 Dutch construction practitioners who engage in SCM. These professionals have diverse roles, e.g. investors, contractors, architects and consultants. Totally, 29 different AEC firms were initially contacted. Next, 14 SCM projects with BIM adoption were evaluated for use in this study, as to timing and availability. This sample was further reviewed to identify cases that fulfilled the following selection criteria with diversity:

- Type: Building construction: multifunctional (MF), housing or utility.
- Scale: Small (up to 2,000 sqm) to large (more than 20,000 sqm) projects.
- Team: A multi-disciplinary SC partnership that is composed from at least a design team, a contractor and a client/owner organisation.
- History: The partnership has been active for at least one other project.
- Vision: The partnership expresses a clear vision for future collaboration.
- Technology: Use of BIM-based tools from at least one SC partner.

From the 14 projects, five cases were shortlisted for further exploration, since they complied with the selection criteria, fit an appropriate research timeframe and offered the desired diversity. In all cases, the contractors were the initiators of BIM adoption and SCM practices. All projects were studied between Definitive Design and construction Preparation, during the first half of 2015. For confidentiality the selected SCM projects are mentioned as A, B, C, D and E (sorted in chronological order of recruitment). Table 1 shows an overview of these five selected SCM cases:

Table 1: Compliance and variety of the BIM-based SCM projects to the case selection criteria.

	Type	Scale	End date	SCM use	History	Vision	BIM use	Extent
A	MF	Large (L)	02/2016	Yes	2 projects	Unclear	Yes	Local
B	Housing	L	12/2015	Yes	All projects	Yes	Yes	National
C	Utility	Mid-(M)	10/2015	Yes	All projects	Unclear	Yes	National
D	Utility	Small (S)	10/2015	Yes	All projects	Yes	Yes	National
E	Housing	M	08/2015	Yes	3 projects	Yes	Yes	Local

Seuring *et al*. (2005) claim that case study is among the standard research methods for SC research. Since a SC is a distributed system, an equally distributed method of data collection from interviews and questionnaires was used to maximise the exploration of the topic. The selected case study design shifted away from the traditional research on the *"focal"* firm of the SC and devoted about equal time to all SC partners (from top management to modellers). The projects were periodically and discretely followed and in total five chains with 44 professionals from 31 different firms were interviewed.

The data collection method (interviews and questionnaires) was first tested in a pilot case study during the first quarter of 2014 and later amended to assure question validity and compliance to research goals. Semi-structured interviews with all SC actors (5-10 actors per project) were used. There were three data collection phases:

- Phase 1: SCM analysis: Questions about the strategy, history, vision and application areas of the SC addressed to the top management (internal SC);
- Phase 2: BIM analysis: Questions on BIM adoption and BIM application areas addressed to the whole SC (including the external SC partners);
- Phase 3: BIM analysis: Attended *"BIM meetings"* among the whole SC.

Since the five projects are currently ongoing, the paper analyses only their SCM and BIM aspirations and their collaboration routine during the initial stages. The authors retain reservations as to the final outcomes of the projects, since for some, BIM is a recent entry and their collaboration routine may be revised. The selected methodology provided an overview of the SC status, goals and BIM use in BIM-based SCM cases. Afterwards, the cases will be followed for a total period of maximum 1.5 years, depending on the scale, to detect the full impact of BIM-enabled SCM practices.

SCM DESCRIPTION AND ANALYSIS – PHASE 1

The studied projects had various SC team compositions spread along the different project phases. The partners varied per project based on the technical requirements and investment ambitions of the SC. In all projects, the contractor was internal member of the SC. The rest of internal SC members were found in both the forward SC part (from initiation to design), e.g. clients and designers and the backward SC part (from construction to operation), e.g. installation firms and suppliers. The rest of the involved actors (apart from the contractors) per project are as follows:

- Project A: The structural engineer, energy advisor, heating, energy and plumbing firms and facility manager were internal SC members.
- Projects B, C and D: The architect, structural engineer, steel sub-contractor and few suppliers (e.g. windows, roof) were internal SC members.
- Project E: The structural engineer, heating engineering and installation firm and client and facility manager were internal SC members.

As regards the project stages with SCM application, there were various configurations according to the project history and underlying SC strategy. In particular, SCM was applied in the following stages of the projects:

- Project A: SCM was applied from Preliminary Design until Operation phase. The project was initiated as Design-Bid-Build.
- Projects B and D: SCM was applied from Initiation until Operation.
- Projects C and E: SCM was applied from Schematic Design until Construction phase. No plans were made for Operation and Maintenance.

A diverse sample of BIM-based SCM projects was collected. Table 2 illustrates the levels of SCM maturity. The first column to the left contains the project identifiers (A, B, C, D and E). The columns include SCM maturity factors adapted from Vrijhoef (2011). The cells contain the descriptions *"Yes"* and *"No"* when a particular SCM application area is or is not present in the case, respectively. The last column to the right relates the overall SCM maturity according to the total number of factors present in each case (data in the column on the left of the last) with Ad hoc, Defined, Linked, Integrated or Extended types, adapted from Lockamy III and McCormack (2004).

Table 2: Factors of SCM applications per case (column list adapted from Vrijhoef (2011)).

	Integration of business activities	Partner sourcing	Integration of operations	Logistics control	Quality management	Information exchange	Product design & development	Market approach and marketing	Cultural alignment	Human resource management	Total number of present factors	Overall degree of integration
A	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	8/10	Linked
B	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	8/10	Integrated
C	Yes	Yes	No	Yes	No	Yes	No	Yes	Yes	No	6/10	Linked
D	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	8/10	Integrated
E	No	Yes	No	Yes	No	Yes	Yes	No	No	No	4/10	Defined

BIM DESCRIPTION AND ANALYSIS – PHASES 2 AND 3

BIM adoption in BIM-enabled SCM practices

BIM was adopted with various nuances throughout this study. BIM was used in the Preliminary Design (PD), Definitive Design (DD) and Technical Design (TD) phases for every SCM project. At times, BIM was used in construction (projects A, B and D), while BIM-based operation was allegedly doable in some SCM projects (A, B and D).

BIM has various applications in AEC according to Cao *et al*. (2014). Yet, BIM was used in only a few of the acclaimed application areas in the studied projects. Table 3 presents an overview of these applications per case. The first column to the left contains the project identifier. The table cells contain the descriptions *"Yes"* and *"No"* when a particular BIM application did or did not take place, respectively, in the project. Overall, most applications of BIM were found in: 3D representations, design coordination, clash detection and quantity take-off. Rarely, they used BIM for cost estimation, energy simulation and site management. The last column indicates the equivalent BIM maturity level, according to UK National standards (GCCG, 2011).

Table 3: BIM application areas per SCM project (column list adapted from Cao et al. (2014)).

	Site analysis	Design exploration	3D representation	Design coordination	Cost estimation	Energy simulation	Clash detection	Construction system design	Schedule simulation	Quantity take-off	Site resource management	Offsite fabrication	UK BIM maturity
A	No	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	No	Level 3
B	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	No	Level 3
C	No	No	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	Level 2
D	No	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	No	No	Level 3
E	No	No	Yes	Yes	No	No	Yes	No	No	Yes	No	No	Level 2

Actual SC collaboration via BIM

After attending their *"BIM and Design"* meetings, the five SCM projects were found to display three levels of BIM-based collaboration. These were encoded as *ad hoc*, *linear* and *central*. The next paragraphs present them in increasing order of integration by describing their characteristics per project that displayed them.

Ad hoc BIM collaboration was observed in project E. Only some SC actors used BIM and the contractor was responsible for coordinating their BIM models occasionally by exchanging proprietary BIM models. Also, the exchange of traditional means such as prints of 2D drawings, frequently and iteratively, was greatly encouraged.

Linear BIM collaboration process was observed in projects B, C and D. Most actors used BIM, apart from some suppliers. The BIM collaboration took place by merging segregate models to one with model checker software, via IFC. Yet, the collaboration was linear, since the contractor (who was in charge of model merging) had individual and on-demand BIM sessions with each SC partner and informed the rest by email.

Central BIM collaboration process was observed in case A. The contractor was responsible for merging segregate models weekly with model checker software. The coordination of their activities was achieved by hosting regular joint BIM meetings fortnightly. The client organisation (albeit not an internal SC member) also attended the sessions to stay updated and ensure their needs were met.

INTERPRETATION OF THE OBSERVATIONS

Impact of BIM on SCM practices

BIM adoption has irreversibly changed the relations and organisational structures not only to one firm, but also to the whole SC. The 42% of firms (13 firms) who took part in the study claimed that adopting BIM was an internal decision (often taken in 2000) to serve their intra-organisational needs for advanced ICT. Most firms adopted BIM during 2005-2008. The rest interviewed firms (58%) claimed that BIM adoption was an external but natural decision, since they had to meet client and market demands.

BIM skills are often a criterion for partner selection when forming the SC. In case E, they performed an unofficial competition (with brief and presentation) among their past preferred partners to select the most BIM-savvy partner. In cases B and D, process quality, which entailed BIM use, was superior than price, for partner selection.

In the study, the BIM-using firms also used it in about half of their projects, included it into their business plans and advertised their BIM-readiness. Yet, since their BIM project portfolios contained 1-4 projects, there were various levels of BIM skills in the SCs. In decreasing order of BIM experience, the SC of project E had two past BIM-based projects, A had one and B, C, D had sporadic BIM applications respectively. Thus, the BIM-readiness of the SC further relied on the BIM-readiness of the partners.

Impact of SCM on BIM practices

BIM changes the collaboration within SCM practices. The partnerships were retained and supported, even if non-BIM using partners participated. This held true in all cases. The outliers either followed a traditional process or were learning on-the-job. The BIM-using partners of cases A and E helped the less experienced partners during extra sessions. In the rest, the BIM challenges were solved informally and on-demand.

Written regulatory agreements are popular within SCM practices. The studied cases used customized BIM protocols based on BIM norms issued by the Dutch Building Agency. The SC partners used such BIM protocols to define their BIM process aside the existing SC contracts, which defined their obligations and rewards. The cases A, B and D customised the BIM norms to their particular traits and needs. These protocols included a description of their particular BIM goals, modelling stages, Level of Detail (LoD), timelines, deliverables and directions for their physical interactions. Thus, their BIM collaboration was enriched by contractual means also present in SCM practices.

Apart from written agreements, the SCM practices influenced the physical BIM collaboration. In cases A, B and D one or more joint meetings with all partners were held, i.e. *BIM meetings*, *BIM Design and Engineering meetings* or *BIM Design sessions*. These meetings resembled a lot to pull-planning sessions (which were also included in cases B, C and D) as to the established underlying trust and pursuit of mutual gains and understanding. Their periodicity, duration and any special sessions were set in the BIM protocols. The BIM meetings were usually obligatory for all – so as to share their information –, held weekly or fortnightly and lasted about two hours. The contractor of case A hosted further regular, weekly and optional *"BIM sessions"* for calibration.

Cumulative impact of BIM-enabled SCM practices

The explored cases offered insights into the adoption of BIM-enabled SCM. Table 4 summarises the previous observations. The first column to the left contains the case identifiers. The next shows data on project type and scale. An analysis of BIM use as to the actors, applications and collaboration is shown afterwards. The next three columns show SCM adoption as to the actors, applications and maturity. A mismatch was noted between the level of BIM collaboration and SCM maturity. Case A featured advanced BIM-based collaboration, even if the SC was young and vice versa: mature chains used BIM without utilising its full potential (e.g. B, D). The last column to the right contains an estimate based on these mismatches. *Central* BIM collaboration and *integrated* SCM practices are both elements of *promising* practices, even if BIM and SCM use was *linear* and *linked* respectively (e.g. A, B, D). Case C was deemed *unclear* due to existing risks that did not allow for integrated operations (Table 2). Case E was considered *poor* example of BIM-enabled SCM, as *ad hoc* collaboration could support neither integrated building information nor further SC integration.

Table 4: Findings of the analysis of the selected projects with BIM-enabled SCM practices.

	Description (Type and scale)	Actors using BIM	BIM application areas	BIM collaboration process	Actors of SCM	SCM application areas	SCM maturity	BIM & SCM overview
A	MF; L	9/10	7/12	Central	7/10	8/10	Linked	Promising
B	Housing, L	9/11	7/12	Linear	9/11	8/10	Integrated	Promising
C	Utility; M	5/8	5/12	Linear	5/8	6/10	Linked	Unclear
D	Utility; S	5/9	6/12	Linear	5/9	8/10	Integrated	Promising
E	Housing; M	6/8	4/12	Ad hoc	4/8	4/10	Defined	Poor

These case studies are ongoing and the authors refrain from generalising. The study goal was to explore the current status of BIM and SCM combination in industry. One study limitation is that for proximity, all projects were based on the Netherlands. Yet, useful lessons could be extracted for other countries as well.

DISCUSSION

Changes in the SC relations from BIM adoption

The traditional SC was formed by the interplay of price and trust (Segerstedt *et al*., 2010). The contemporary SC is formed not only as to price, delivery or quality, but also as to their BIM-readiness. In cases A, B, E, the firms sought equally BIM-skilled SC partners, perceiving BIM as a unique selling proposition. The contractor and client were dedicated BIM-aspirers, apart from drivers of SC integration (Ling *et al*., 2014).

The numbers of involved stakeholders in a project constantly increase (Zavadskas *et al*., 2010) and simultaneously their existing roles change. Their relations transform from adversarial to symbiotic in the light of achieving the reported benefits from BIM adoption (Azhar, 2012, Barlish and Sullivan, 2012, Bryde *et al*., 2013, Hartmann *et al*., 2012). The following list includes the new and amended roles (from BIM-enabled SCM adoption) of the most influential actors as seen throughout the five SCM cases:

- The client aligned to the market demands and requested BIM-enabled project delivery but rarely had a strategy for using BIM during operation.
- The contractor was the BIM-integrator, used it for audit and often offered the basic infrastructure (physical and digital) for BIM-based collaboration.
- The design and engineering team was the BIM forerunner. All architects and structural engineers were BIM-proficient in the studied projects.
- The sub-contractors were tech-savvy and efficient with BIM, since most of them were familiar with building product models before the debut of BIM.
- The suppliers were starting to adapt very competitively in the BIM process.

Advantages and limitations from combining BIM and SCM

Azhar (2012) claims that early engagement with BIM is doable, yet in the study it was mostly used in design and construction. This *"late"* adoption could be related either to the usually less BIM-proficient project initiators (e.g. client, user), or the fragmented AEC lifecycle just before the permission stage (e.g. project A) that allowed for delays.

The BIM collaboration in SCM projects was achieved through aggregate reference models. The collaboration was mostly supported by other types of interaction, e.g. physical meetings, since it is in fact asynchronous, as Cerovsek notices (2011). The BIM protocol assisted the definitions of *"what"* to exchange, LoD and modelling stages. The SCM practices, shared history and experiences among the SC actors enriched the definitions of *"how"* and *"when"* to interact, e.g. issuing specifications and hosting regular and special physical meetings. The intuitive SCM practices also promoted co-design and the emergence of shared BIM vision via team collocation (cases B, C, D). The main BIM benefit for SCM was the continuous information flow and the main SCM benefit for BIM adoption was the collaboration in a trustful setting.

Despite the benefits from BIM-enabled SCM, some challenges were reported. The actors of the projects A, B, C and D required denser interactions from time to time. Another recurring issue was the ownership of design in certain design tasks. They repeatedly asked: *"Who draws what?"*. The collocation, which was encouraged by the SCM practices, perfectly resolved such doubts. Therefore, BIM and SCM practices complemented each another and gradually overlapped. Yet, the younger chains were more BIM-savvy and vice versa; the mature chains displayed a rudimentary BIM-based collaboration routine and they relied more on their SCM relations: common experience, shared background, expertise and familiarity. To devise an evaluation of the various BIM-enabled SCM configurations; *promising*, *poor* and *unclear* descriptions were given (Table 4). An additional hypothesis is that *integrated* SCM practices could support a *central* BIM-based collaboration in the future.

The discovered BIM collaboration patterns– *ad hoc, linear*, and *central* – might also be applicable to non-SCM settings. The recruitment of these BIM-enabled SCM projects was facilitated by the already organised SC actors in partnerships and their collective decision to share information for research purposes. After all, the promise of BIM for integral information aligns to the need of SCM for regulated information.

CONCLUSION

This study investigated the influence of BIM upon forming and supporting SCM practices in AEC. First, it identified that BIM-proficiency was important aspect of partner selection. Moreover, the level of the actors' BIM-proficiency shaped the type of BIM-enabled SCM collaboration processes. The BIM-enabled SCM routine included written agreements and frequent physical interaction that greatly resembled

SCM contracts and joint sessions respectively. Second, the paper identified ad hoc, *linear* and *central* BIM collaboration processes. Using BIM with *central* collaboration from design until operation was the most promising and smooth route to reach the full potential of SCM practices. Yet, a *linear* collaboration process sufficiently supported small and simple projects when combined with integrated and mature SCM.

A diverse sample of Dutch SCM projects was explored and it was concluded that SCM theory is fully supported by BIM, which in turn provided the mature SCM configurations with integration of information flows. Simultaneously, BIM adoption was enriched by SCM theory so as to perform in its full potential, as described above. Yet, there was a mismatch between the extent of BIM collaboration and SCM maturity, which could be improved by more frequent interactions and peer BIM trainings. Overall, BIM was used as an inclusive design and information platform, but had not yet reached its full socio-technical maturity, which could be activated and supported by applying it in teams with already achieved trust, i.e. SCM environments.

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