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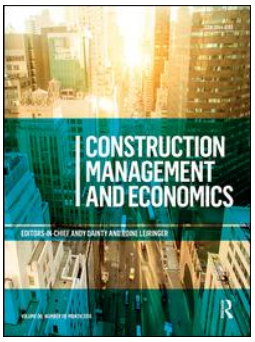

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A holistic analysis of a BIM-mediated building design process using activity theory

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ABSTRACT

Building Information Modelling (BIM) is said to hold potential for increasing efficiency of the design processes in the building industry. However, designers struggle at times to apply the different BIM-tools. In order to understand this disjoint, it is necessary to understand first the existing practices of different specialists in the building design process in order to improve future development and implementation of BIM. The aim of this article is to investigate the consequences of using BIM-tools in a collaborative building design setting consisting of different specialists. A case study was carried out to trace when BIM-tools were used (or not) in an inter-organizational design process of a naval rescue station in Denmark. The design process was holistically examined through the lens of Activity Theory which is an analytical framework. Five key findings were identified: the mediating role of 3D visuals, real-world coupling with point cloud, rule-breaking to ensure design completion, inability to integrate BIM-analysis into the design and the use of heuristics to form and choose among design solutions.

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Building information modelling; building design; case study; activity theory

Introduction

Creating a building design that involves the integration of Building Information Modelling (BIM)-tools is a complex process since it requires input from multiple specialists. To better understand how BIM-tools are used in the building design processes, we conducted an in-depth investigation to identify the consequences of such an activity.

It is quite common that substantial amount of errors are made during the design stage of a building project, which increases the overall building projects cost (see, for example, Lopez and Love, 2012, Peansupap and Ly, 2015, Shamsudeen and Biodun, 2016). Lopez and Love (2012) found that the cost of the direct and indirect design errors was on average 6.85% and 7.6%, respectively. Another study done by Flager and Haymaker (2007) found that building designs were only iterated 2.8 times on average because of inefficient processes that could decrease the designer's opportunity to optimize the design. The building design process can be described as a process of exploration where the designers search for, identify, choose, assemble and specify a design within a *space of possible solutions* (Logan and Smithers 1993, Gero 1998). However, humans, like the designer, have limited cognitive abilities to process large and complex networks of consequences that one solution may have compared to another (Miller 1956, Kleinmuntz 1985, Simon 1991). Without the support of tools to present and externalize the design intent and consequences, designers will need to rely on their internal mental abilities to assemble the solutions into a design. Dorst (1996) and Simon (1957) pointed out that this may lead to difficulties to handle the complexity of *space* resorting to using heuristics techniques, like *satisficing*, where people tend to select the first and apparent option (Simon 1957) in difficult decision-making situations. However, it has been reported that satisficing often leads to poor performance solutions (Kleinmuntz 1985).

BIM is considered one of the solutions to improve the process of design (Krygiel and Nies 2008, Eastman *et al*. 2011, Demian and Walters 2014). It is argued that using BIM-tools to mediate the design can support the exploration of *the space of possible solutions* and lessen the need for satisficing by allowing for faster, more accurate and consistent evaluation of the design performance (Krygiel and Nies 2008, Eastman

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et al. 2011, Bryde *et al.* 2013). The creation of BIM-models enables the possibilities to coordinate the design and to use BIM analysis tools to predict the consequences of the solutions. Surveys indicate that the use of BIM-tools is becoming the standard approach for designers to mediate the creation of building design in multiple nations (Bernstein *et al.* 2014, Malleson and Watson 2016, Waterhouse and Philp 2016). In one account, United Kingdom companies are close to having reached Level 2 BIM, which indicates that BIM-models are used in a federated model to better exchange information in projects (Waterhouse and Philp 2016).

The use of BIM-tools is considered a complex topic which demands new understandings of what building design actually is (Oxman 2006). Organizations and BIM-tool developers are still figuring out how best to use it and further develop it to be integrated into the design practices (Malleson and Watson 2016). Dilemmas occur because of the introduction of new technology in old practices. The benefits of the technology are first properly achieved when both the practice and the technology are in the balance, limiting the dilemmas of its use. Notions of the interplay between BIM and the practices are, therefore, of high importance in the attempt to understand how such balance is achieved.

In a recent article by Miettinen and Paavola (2014), it is argued that research often neglects the unique characteristics of how users adopt the use of BIM and that research that concentrates on a predominantly normative approach tends to portray such activities as too optimistic. The normative approach is defined as a way to optimize the efficiency and economy of technological systems by experimenting with the best parameters for operating a system (Miettinen and Paavola 2014). This critique is extended in other research such as Harty and Whyte (2009), Neff *et al.* (2010) and Kokkonen and Alin (2016) who also call for qualitative research to complement the normative studies of BIM practices. Other studies have already contributed to improving the understanding of how BIM is used in practice, each focusing on individual aspects of using BIM, for example; representation (Bouchlaghem *et al.* 2005, Whyte *et al.* 2016), collaboration (Kerosuo *et al.* 2013, Kokkonen and Alin 2016, Poirier *et al.* 2016), interaction (Oxman 2006) and decision-making (Schade *et al.* 2011). However, there are only a few studies that attempt to provide an in-depth and holistic analysis of how BIM is used in the design process.

In this article, we seek to contribute with a holistic account of how BIM is used in a design project. The research question is: what are the consequences of using BIM-tools to mediate the building design process in a collaborative design environment? We hypothesize that the use of BIM-tools for feedback in the design process may improve the building process overall (through new opportunities for a more efficient design process that aids the designers in design exploration that reduces the need for satisficing and to make more informed choices). To address the research question, we have investigated a single case study of an intensive building design workshop, organized to apply BIM-tools. The empirical material from observations was analyzed using Activity Theory as a framework assisting in achieving a holistic perspective (Kaptelinin and Nardi 2012). One of the benefits of using Activity Theory for a holistic analysis is its top-down approach of analyzing how activities play out between people, intentions and technology (Kaptelinin *et al.* 1999).

BIM-tool use in practice and ways of analyzing it

It has been established that the use of BIM-tools in practice is sensitive to the complex forms of social and individual activities (Kerosuo *et al.* 2015, Vass and Gustavsson 2017). People's usage of tools is shaped by cultural norms, values and regulations when doing work, which can result in rejection or the inefficient use of these tools (Nardi 1996). The role that digital tools play in supporting designers in the design process was theorised by Oxman (2006) who suggested that these tools allow designers to interact with their design. Oxman focused on the individual interaction with design activities such as generation and evaluation through design tools. However, such activities can be difficult to track in design projects due to the distributed way of working in the construction industry. An attempt to better track the designers' interactions with their design was proposed by Whyte *et al.* (2016). The authors suggested that the connections between different design representations (e.g. BIM-models, paper drawings and physical mock-up models) should be tracked across time and disciplines to reconstruct practices and observing their effects on the design. The authors used Actor-Network Theory and Latour's (1986) notions of how designers' visual representations develop their understanding of design as their theoretical framework. Tracking people's evolving interactions through representations of their design products (e.g. 3D model, drawings) allowed identifying how representations were used across locations and time. In a study by Neff *et al.* (2010), data from a case study were used to analyze how people utilized digital models, based on the idea of boundary objects (Star and Griesemer 1989), to foreground the evolution of design in relation to communication and collaboration between different specialists. Concentrating on boundary objects means that the design product becomes a central object that exists at the boundary between different specialists, iterates between them and is changed by their different inputs. In this study, we were interested in using the analytical framework of Activity Theory that is explained next.

Using activity theory to study the application of BIM-tools in building design

Activity Theory has widely been applied in a broad range of domains including learning, organizational and Human-Computer Interaction studies. However, only a few studies have been conducted that were using it to analyze the use of BIM-tools (Mäki and Kerosuo 2014, Kerosuo *et al*. 2015). Activity Theory can assist when a holistic analysis approach is desired since it places emphasis on identifying human intentionality and its impact on the interactions that involve the use of technology. In Activity Theory tools such as BIM are examined by looking at the motivations of the people using it, unlike in Actor-Network Theory (Whyte *et al*. 2016) where networks of people and technology are considered being symmetrical. Activity Theory is argued to provide a more holistic analysis since it draws attention to the difficulties with information systems implementation, focusing on the complex social practices of people who are interacting to create a design (Miettinen and Paavola 2014).

Activity Theory is a sociocultural theoretical framework used to conduct qualitative analyses for understanding cultural and institutionalized practices. Activity Theory, as a method of analysis, pays attention to the interactions that unfold when people use particular tools in the pursuit of a specific goal (Miettinen *et al*. 2012). The theory assumes that studies of people's activities cannot be reduced to assessing individual or internal processes only and allows for the close examination of the interactions between human subjects and the world around them (Engeström 2005). Activity Theory takes note of the instruments that mediate the pursuit of goals and in doing so it foregrounds the transformations that occur as a result of this engagement (Nardi 1996). Such transformations may be desired, planned or not, and allow a researcher, upon closer inspection, to take note of intentionality, history, mediation, collaboration and development (Nardi 1996).

Activities are seen as high-level abstractions and are the unit of analysis in Activity Theory (Kaptelinin and Nardi 2012). In an activity, human subjects are motivated to transform their *motives* of achieving a goal (e.g. the design of a building) by taking *actions* that are operationalized (e.g. making a design decision). A simple example would be the motivation for designing a house (an activity). This motive results in specific actions such as the creation of a building design, which is operationalized by sketching on paper. *Actions* are described as all the steps taken in pursuit of a particular object (e.g. search for, identify, choose, assemble and specify a design), including the unconscious steps (e.g. when walls are drawn they define and limit the size of a room). Since actions move in the direction of pursuing a particular object, they are defined as object-oriented (Engeström 2000). Operations, in contrast, describe the routine processes that allow for the adjustment of an action. The object of an activity is embedded within the motivations of individuals and related communities (Engeström 2010). Activity Theory also allows for the analysis of the social aspects that shape activities (Engeström 1987) including rules (the cultural and organizational rules affecting the activity), community (various communities affecting the activity) and division of labour (the division of activities among subjects in the system).

The instrument or tool plays a central role in a subject's ability to realize a goal, thereby transforming the object into an outcome of the activity. Béguin and Rabardel (2000) argued that the instrument used in an activity is a composite entity based on both the subject (user's cultural history of using the instrument) and the object (what is to be transformed). The composite entity consists of an artefact structure (material or symbolic) and a psychological structure, which is used to organize an activity. For example, BIM-tools are used based on their functional capabilities (artefact structure) and how the subject chooses to organize the activity to transform an object. This composite nature of the instrument mediates the subject–object relationship in activities (Béguin and Rabardel 2000).

The success of the transformation of the object of a design activity may be hindered by what is described in Activity Theory as contradictions, which is explained next.

Contradictions and how they are manifested

In Activity Theory, situations that cause problems or the breakdown of activities are described as contradictions. Engeström (2001) explained that contradictions are historically accumulated tensions that can exist within and across activities. When contradictions occur they typically enforce a response, for example, a reflection, on how to continue pursuing the goal of the original activity. Engeström (2001) argued that the key to Activity Theory is understanding contradictions since they reveal how activities transform (Engeström 2000, 2010).

In order to identify contradictions, it is necessary to understand that contradictions manifest themselves as dilemmas (Bonneau 2013). Dilemmas are defined as expressions of incompatible evaluations, for example, ethical choices that have to be made to identify the benefit for either the client or the user, or the dilemma of choosing a window based on aesthetics, sustainability or price. Dilemmas are often multifaceted and subject to the components of the activity and can happen at the individual level or amongst groups of people. When people work together they often try to overcome the tensions that were created by dilemmas (Deken and Lauche 2014). This cooperation is achieved by aligning, integrating or even innovating their work practices. However, simple transfers of practices are often impossible since they happen through accidental or deliberate improvisation (Orlikowski and Yates 1995). Identifying the contradictions within an activity provides fruitful points of entry to understand the kinds of issues people experience and the nature of negotiations or measures they take to alleviate them.

Methodology

In this study, a case study was analyzed using Activity Theory to investigate how BIM mediates design practices holistically. Case studies are most suitable for research that concern complex phenomena in real-life contexts (Baxter and Jack 2008) that are hard to study out of context (Runeson and Höst 2009) and where researchers have less control over the events (Yin 2009). Applied correctly, case studies can assist the systematic study of expert knowledge and practices (Flyvbjerg 2016) if they base their conclusions on multiple sources of evidence (qualitative and/or quantitative), that was collected consistently, and add the resulting new insights based on established theory (or the lack of) (Runeson and Höst 2009). Using a case study, methodology and an Activity Theory framework for analysis allowed a systematic and organized focus on gaining a contextualized understanding of expert practices.

The case – design of a naval rescue station

We followed a design project that was tendered by the Danish Defence Estates and Infrastructure Organisation for a new naval rescue station and associated quay in Northern Denmark. The Danish Defence Estate organized the design process as workshops with help from hired workshop facilitators. The setup of the workshop was experimental and deviated from traditionally organized projects. Traditional projects do not require that diverse expert teams work together at the same time and in the same space. This method of project design has been critiqued to cause a fragmentation of knowledge transfer (Lindner and Wald 2011, Fulford and Standing 2014). Therefore, the project design in this study adopted a workshop format that was facilitated as a collaborative environment similar to the big room (AIA 2007) to support concurrent engineering (Kamara *et al*. 2007). A team of specialists was hired to participate in a collaborative environment and to give the specialists support in their decision-making was BIM-tools used to improve the representation and analysis of the design. Emphasis was placed on creating a collaborative environment to optimize opportunities for participants to contribute their insights supported by the BIM-tools. Incentives were created to diminish the traditional boundaries of service to motivate the participants to create the best building to reduce the risk for potential legal, political and management issues such as responsibility and ownership of information (e.g. the specialists was hired from a single consultancy firm).

The goal of these workshops was to develop a design from an initial design specification and turn it into a preliminary project. The workshop facilitators created a scorecard based on the clients' and users' needs that were formulated before the workshops in the initial design specification. Seven indicators were used; cost, design aesthetics, constructability, sustainability, building code requirements, time (to construct) and design quality. Sustainability was based on the Danish sustainability assessment method DGNB (GBCD 2014).

A decision was made by the facilitators to focus on three performance indicators to be evaluated through three commercially and widely used BIM-tools in the Danish construction industry: aesthetics, cost and sustainability. Lumion (2017) was intended to be used for assessing design aesthetics, Vico Office (Vico Software 2017) was intended to be used for assessing the cost of the building, and Ecotect/Green Building Studio (Autodesk 2017a) was intended to be used for assessing sustainability. Autodesk Revit 2014 (Autodesk 2017b) was used to generate the BIM-models, where Revit BIM templates that included building objects like windows, doors and walls were prepared. Moreover, a method for classifying the BIM objects used to design the BIM-models that intended to improve the use of,

Table 1. The intended use of BIM-tools and other related tools in the workshop.

Tools used in the workshop	Tool category	Indented output
Autodesk Revit	BIM Authoring tools	2D documentation of the design and a BIM-model to be used by visualization and analysis tools.
Point clouds	Reality capture tools	To be used as a reference of the buildings existing environment and interior.
Lumion	Visualization tools	Visualizations for the project participants to inform the project KPI's.
Vico Office	Cost analysis	A cost analysis to inform the project KPI's.
Ecotect (Green Building Studio)	Sustainability analysis	A sustainability analysis to inform the project KPI's.

Table 2. Overview of participants in the workshop.

Workshop participants	Organization
Client	Danish Defence Estate
Client	Danish Defence Estate
Client	Danish Defence Estate
Facilitator 1	BIM advisory company
Facilitator 2	BIM advisory company
User 1	Rescue Station Personnel
User 2	Rescue Station Personnel
Client Advisor	Design consultancy company
Architect	Design consultancy company
Cost-specialist	Design consultancy company
Structural engineer	Design consultancy company
Sustainability-specialist	Design consultancy company
BIM-modeller 1	BIM-modelling institution
BIM-modeller 2	BIM-modelling institution
BIM-modeller 3	BIM-modelling institution
BIM-modeller 4	BIM-modelling institution
BIM-modeller 5	BIM-modelling institution

e.g. Vico Office was prepared. The classification of objects was intended to help the designers ensure that the correct quantities from the BIM-models were used to represent the right quantities in Vico Office, increasing the validity of the cost estimation. Point clouds were made of the existing conditions before the workshop took place. The scans included the existing building, its inventory, and its site and were loaded into the BIM-authoring tool. An overview of the used BIM-tools can be found in Table 1. The use of the BIM-tools was aimed to inform the KPIs to enable the workshop participants to make better design decisions and to improve communication by enabling faster expressing of solutions in the BIM-model and faster assessment of the performance impact of the solutions.

The workshops were initiated with a start-up meeting introducing the setup of the workshop presenting the KPIs. Afterwards, the participants gathered to initiate the design meetings and started formulating and negotiating potential solutions. When something was ready to be manifested, such as a solution related to the layout of the building, the BIM-modellers interpreted and expressed the participants' solutions. When the BIM-modellers had manifested the solutions in the BIM-model, the participants gathered to discuss the solutions further. The participants would move between the meeting table away from the BIM-modellers and back to the BIM-modellers' projector screens throughout the workshops. The intended outcome from the clients was that the workshop would result in a design that was evaluated with the KPIs informed by the BIM-analysis tools and documented sufficiently for the building authority to assess the design for building permit. The workshops were conducted over 3 months with four workshop-sessions, including three 1-day workshops and one 2-day workshop. All of the workshops were observed.

Workshop participants

The designers participating in the workshop were hired through a consultancy company. The design consultancy company sent five design specialists to accommodate the needed services as well as to participate in the workshops. They were a client advisor, an architect, a cost-specialist, a structural engineer and a sustainability-specialist. To assist the specialists, BIM-modellers were invited from a BIM-modelling institution to share the advantages of using BIM. This way of organizing the setup was done to ensure that the users of the BIM-tools possessed the necessary level of BIM education and were familiar with the capabilities of the BIM-tools. The BIM-modellers manipulated and assessed the BIM-models according to the instructions of the specialists. Besides the clients, facilitators, specialists and BIM-modellers, the users of the building participated. Table 2 shows an overview of the participants. The participants all joined in the workshop and received the initial design specifications before the first meeting.

Data collection and processing

Systematic participant observation was the primary source of data collection. This included taking field notes, photos, and making video recordings. Moreover, products from the workshop including BIM-model files and 2D drawings were collected. All participants had provided their informed consent for this kind of data to be collected from them. 30.5 h of video recording was captured, downloaded and analyzed. To ensure a systematic analysis of video recorded material the event-logging software

Behavioural Observation Research Interactive Software (BORIS) was used for video coding (Friard and Gamba 2016).

The data were coded with a main focus on the mediating role of various BIM-tools. The coding was conducted according to Activity Theory by identifying dilemmas and resulting actions, and/or changes to the object of design. We used Bonneau's (2013) earlier stated definition of dilemmas as a basis for identifying contradictions. Actions that resulted in design solutions were analyzed to identify what degree they were informed by information produced by the BIM-tools or not. For example, by observing the information produced by the BIM-tools and if they were used actively in making decisions. We analyzed the actions to examine how they led to particular solutions as parts of the object of design. In this way, we identified also any changes to solutions as they manifested in the object of design.

Findings

Through the analysis of the observations, using Activity Theory, a pattern of three main themes were identified and categorized in our findings:

1. 3D visualizations to facilitate the pursuance of design solutions
2. Transformations of the building design through rule breaking
3. Difficulties in conducting performance analysis and evaluation

These themes refer to the different aspects of BIM use in context that surfaced during the analysis of the observed events. We analyzed data stemming from video recordings, field notes, photos, drawings and BIM-models, totalling 1504 separately identified events.

Theme 1: 3D visualizations to facilitate the pursuance of design solutions

The first theme has to do with the transformation of people's ideas into a computer-generated visualization. When the workshop participants congregated next to the computer screens showing 3D models, the joint viewing of these models created at times dilemmas. The reason for this was that the 3D visualizations redefined individual specialists' understandings of the design. In one observation, the users realized that the lookout room was placed too low for the users of the building to get a proper overview of the harbour. This disagreement created the need to solve the dilemmas by finding an agreed upon solution (i.e. action). In the above example, expanding the building vertically to position the lookout room higher was one of these solutions. However, actions to accommodate such needs would at times lead to new dilemmas that needed to be negotiated and required further manipulation of the model.

Key revelations from these observations were that the issues we identified here had to do with managing internalized (mental) ways of problem-solving building design and the resulting disagreements that were manifested in the externalizations through the BIM models. It meant that the resolution of these dilemmas required some degree of social coordination. In another example, the BIM-modellers were creating a layout of the rooms of the building when the architect asked for a design solution to address that there would be different kinds of users of the building who have different needs.

> Architect: "We have visitors that arrive through the staircase to see the lookout room (to the harbour). We need a presentable entrance for the visitors, so they do not interfere with the personnel (rescuers)". (Observation 2, 02:28:00)

This dilemma was pointed out by the architect due to her experience with users of buildings. It meant that the team had to pursue finding design solutions that would satisfy the design constraints, requirements and goals. These moments were important markers throughout the design phases. We found that the 3D visualizations made with the BIM-authoring tool manifested the dilemmas to occur between the participants. Our observations indicated that the clients, users and specialists could explore the design in more detail by asking the BIM-modellers to focus on certain aspects of the 3D visualization as seen in Figure 1. The ability to zoom into specific details of the design model gave new insights into previously unknown or hidden design features, enabling the team to identify those and negotiate actions to address them. Another observation showed that the shifts between perspectives of the building between, e.g. 2D plans and 3D plans mediated the design process and assisted in the spontaneous identification of new dilemmas.

> The architect is arguing about the placement of the control room, pointing at a projected 2D plan view: "We are a bit unsure if it is ok located down here (control room), when the boats are out here (in the harbour) and if you get the view needed on the ground floor. Is it possible to look at it in 3D?"
>
> The BIM-modeller quickly shifted to a 3D representation of the building.
>
> Architect: "Space-wise is it acceptable. But it is just an industrial hall; it is not a pretty building". (01:55 Observation 4)

Figure 1. Picture from the video observation depicting users, clients, specialist designers, facilitators and BIM-modeller designing a building using BIM.

The use of the BIM-authoring tools allowed quick manifestation and dissemination of each participant's design intent. In an observation, the client voiced the need to reuse tiles from the existing building. In order to accommodate this need, the BIM-modellers were able to integrate the reused tiles from the existing building into the new design. This allowed the participants to scrutinize the consequences of integrating the tiles in the new design, which allowed the participants to re-negotiate and solve the dilemma.

In one example, the client wanted to reuse tiles from the old building this was observed to be quickly integrated into the BIM-model and allowed the other participants to scrutinize the consequences of, e.g., aesthetics allowing the participants to re-negotiate and solve the dilemma.

In addition to the use of 3D models of the design, point clouds representing the existing conditions were also used. The point clouds were integrated into the BIM-authoring tools allowing the designers to identify dilemmas during the development of the BIM-models (see Figure 2). The point clouds representing the equipment (e.g. the rescue boat) were used to ensure that there would be enough space in the boat hall. A dilemma arose when the modellers used the point clouds to identify constraints to the shape of the building. The restrictions of the shape would spark new dilemmas for the design team to counter.

Following the coding of the video material and the analysis of the episodes, it was noted that overall, most of the registered dilemmas occurred amongst the participants when they were discussing the 3D visual representation of the BIM-model. 71% (1065 events) of the dilemmas registered were connected to discussions about 3D visualization, 29% (439 events) without. The 3D visualization produced with the help of BIM-authoring tools represented externalized design insights that required at times re-negotiating earlier design decisions and the transformation of mental models into design model manifestations.

Theme 2: Transformations of the building design through rule breaking

On several occasions, it was observed that the BIM-modellers would deviate from previously specified rules regarding the use of BIM. Rules related to the correct use of, e.g., BIM-object and classification. Rule-breaking was observed when participants tried to accommodate the project's timeframe and other constraints. The observations showed that at times the BIM-modellers would improvise and bypass pre-defined rules (e.g. rules of BIM-object classification) of BIM-modelling, to represent real-world objects (which are critical for using BIM-Analysis tools). Such improvisation ensured progress in the creation of the visual model but created problems for the use in analysis tools.

The participants' collective motivation to create a highly developed design in a short amount of time, satisfying the clients was prioritized over the rules for

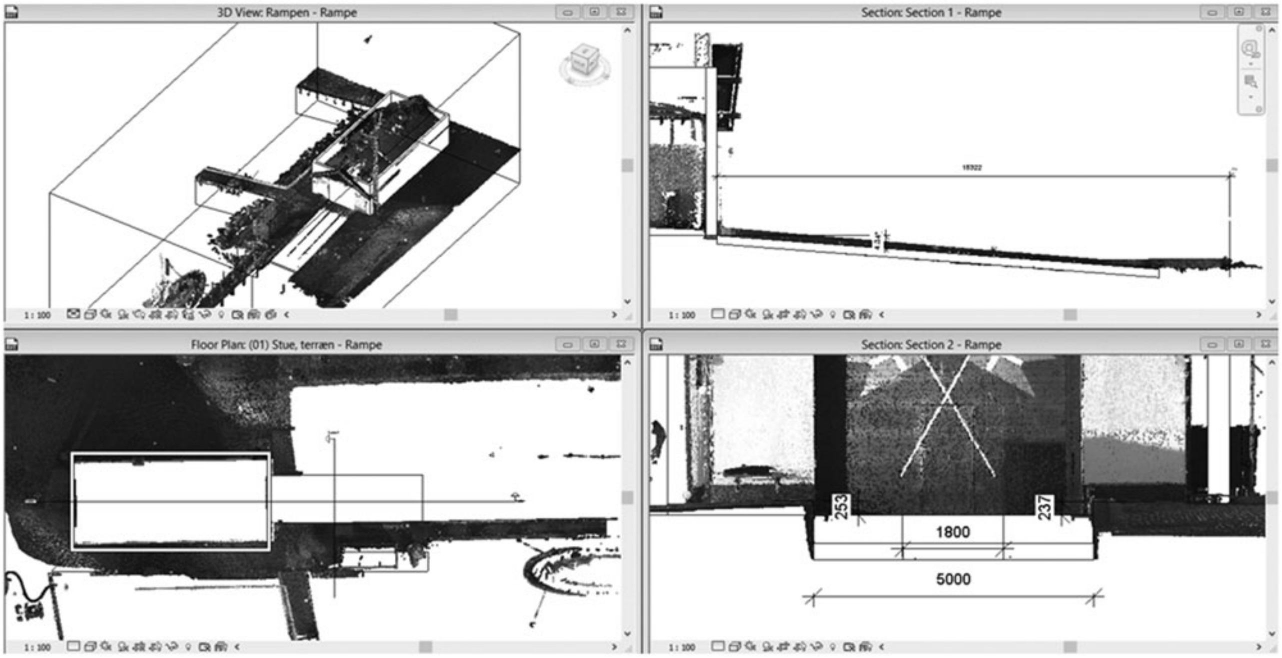

Figure 2. Pictures from the BIM-authoring tool showing how an early BIM-model was used with the point cloud scanning to ensure that distances in the BIM-model matched the distances measured with the point cloud scanning.

correct use of BIM-tools and resulted in creative and sometimes problematic problem-solving. An example of this was when the BIM-modeller followed the architect's instructions for modelling the space layout instead of using the correct (according to the predefined BIM-modelling rules) BIM-objects to represent real-world objects (e.g. use a roof in Revit to represent a roof in real-life). On another occasion, a BIM-modeller used a slanted floor BIM-object to model an existing ramp for the boat to satisfy a specialist designer's need to connect between the ramp and the new building. The BIM-model was developed to meet the immediate needs of the specialist designers but not to be used in BIM-analysis tools. The BIM-modellers responsible for using the BIM-analytical tools had to re-interpret and re-classify the BIM-model for BIM-analysis, which delayed the process and made the results arrive too late to be included in the decision-making. The BIM-modelling rules were created with the intention to allow for correct and quick estimation of the price of the building design. However, the BIM-model went through so much re-work that the price estimation made with Vico Office was out of sync with the development of the design. When the BIM-modellers had corrected the BIM-model (e.g. by properly classifying the BIM-objects), it was obsolete because new decisions had been made in the meantime. It was curious to note that the improvisations and rule-breaking were beneficial for the process since it allowed the design to develop quickly. We frequently observed that the BIM-modellers improvised and adapted to the immediate needs of the participants of the workshop not letting, e.g., BIM-modelling rules slow down the design process.

An important finding in this theme was that we identified a hierarchy in achieving certain design goals. We identified in our observations a hierarchy of goals and that they determined how the design progressed. This meant that breaking certain rules was accepted since it was deemed important at that point in time.

Theme 3: Difficulties in conducting performance analysis and evaluation

Through the design process, the facilitators intended that the BIM-models created during the design activity should be used with the BIM-analysis tools to assess the BIM-model's performance according to the three performance indicators: cost, sustainability, and design aesthetics. These indicators should help focus the design according to the goals, constraints, and requirements of the initial design specification. However, this was only achieved with limited success. Figure 3 shows, for example, that only few performance indicators were identified. While cost was identified (see Figure 3, 'Pris'), the analysis was not generated through the BIM-models but was based on extracted quantities form the BIM-model matched with "experience" based prices by the cost-specialist

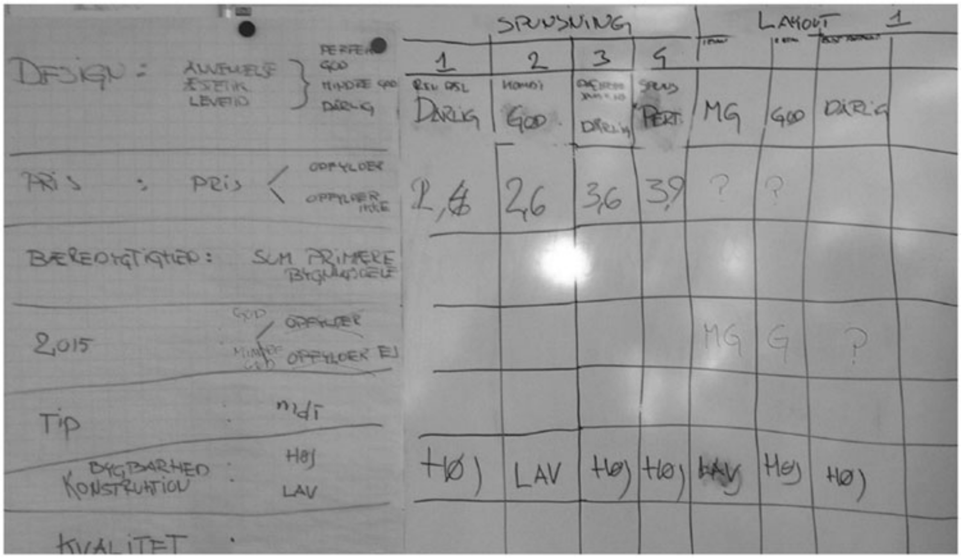

Figure 3. A picture of the near-empty scorecard giving an overview of each of the building solutions' performance. Mainly subjective estimations of the performance were made. From the top left solutions (1,2,3,4 quay solutions 5,6,7 building solutions): design aesthetics, cost, sustainability, energy consumption, time, buildability and quality (Buhl *et al.* 2014).

on paper. Only the design aesthetics indicator was analyzed, based on the visualizations using the BIM-authoring tool.

Besides the planned KPIs, other spontaneous indicators were assessed during the workshop. The BIM-modellers used the scheduling functionality in Revit to collect quantities to inform the participants about general quantities of building objects (e.g. wall, roof, floor and quay quantities) and areas. For example, schedules were created to enable a comparison of the areas in the BIM-model with requirements specified in the design brief.

> Client 1: "The area´s we specified in the building program did they ever get into the model so we could check that the building complies?"
>
> BIM-modeller finding the room schedule in Revit, specifying the areas of the building. BIM-modeller: "It is 447 (m^2)."
>
> Architect: "Is that right?"
>
> BIM-modeller: "Yes".
>
> Architect: "That is not what we calculated it should be 497 (m^2)" BIM-modeller: "Our results are the net area". Architect: "It is too much anyways, approx. 10% too much".
>
> Identifying that the area of the building exceeds the maximum (450 m^2 gross area) specified in the building program.

Lumion was intended to be used to improve the visualization of the BIM-models. However, this had limited success because these visualizations were created only on the last day and were observed to produce no dilemmas. None of the participants found any additional value in the information the visualization produced.

Ecotect was supposed to produce an analysis of the design of the BIM-models to evaluate sustainability. However, the participants did not use the results as an indicator of the design solution's performance in the scorecard shown in Figure 3. The client believed that during the days of the workshop and with the use of BIM, Ecotect would enable the sustainability specialist to produce comparative performance results and documentation of both the DGNB and the legislative requirements of energy consumption.

> Client 1: "I want the solutions printed out" (the results of the analysis)
>
> Sustainability-specialist: "These are the results calculated before we met today. This is the calculation of the energy consumption."
>
> Client 1: "Does this not come out from here" (pointing towards the BIM-model).
>
> Facilitator 1: "No, we can make scenario comparisons."
>
> Client 1: "We have to get the scenarios out, so we can compare each scenario. We already got some scenario calculations" (from Ecotect).
>
> Sustainability-specialist: "We cannot compare the results with mine."
>
> Observation 4 – 03:01:00.

The sustainability specialist argued that the output of the Ecotect analysis software was not applicable to the Danish standards of calculating environmental performance. The results from Ecotect were intended to

Table 3. The actual use of BIM-tools and other related tools in the workshop.

Tools used in the workshop	Tool category	Observed practice
Autodesk Revit	BIM Authoring tools	• Revit used to produce documentation of the design • BIM-models used by BIM-analysis tools
Point clouds	Reality capture tools	• Point clouds used in BIM-modelling process
Lumion	Visualization tools	• Lumion used to create enhanced visualizations of BIM-model but not used for decision making
Vico Office	Cost analysis	• Vico Office used to make cost analysis of solutions using the quantities from the BIM-model • Since results were delayed they could not impact on the decision-making process.
Ecotect (Green Building Studio)	Sustainability analysis	• BIM-models used in Ecotect to produce a sustainability analysis • Results not used for the decision-making process

be used as reference but did not carry much validity. Therefore, the results were not used as performance indicators of the building scenarios, and the results produced by Ecotect were rejected by the sustainability specialist due to a lack of transparency. The clients expressed dissatisfaction with the lack of performance results of the design, due to the extra cost associated with the BIM setup. The clients had envisioned that the results of the BIM-analysis tools would play a larger role in the assessment of solutions. The consequences of implementing BIM-tools resulted in a disjoint between expected benefits and what actually took place.

The BIM-modellers worked with Vico Office throughout the workshops, but the results were not ready in time to be included on the scoreboard as indicators of the solution's estimated cost. The BIM-modellers' improvisations in the creation of the models had created inconsistencies making it challenging to analyze the BIM-models. In the finishing minutes of the last day of the workshop, the cost-specialist expressed:

> Cost-specialist: "We have still not seen the results from Vico (Office)" Observation 5 – 05:19:00

Multiple events were observed using BIM-tools for subjective performance assessments. This meant that the solutions regarding, e.g., building components (such as windows, doors, roofs) were assessed and decided upon using *satisficing*, just like in traditional design projects. The widespread use of *satisficing* to form the design solutions was particularly evident during a conflict that was based on a series of design dilemmas. The actions based on satisficing was used to counter the dilemmas were only superficially addressed according to the facilitator who complained that the participants did not explore enough solutions.

Another observed example of the use of *satisficing* was when the sustainability specialist was constraining the space of possibilities when the participants were trying to find a solution for complying with legislation regarding energy consumption. Decisions had to be made on how many photovoltaic panels were to be placed on the roof to counter an excessively high energy consumption. The participants agreed on a viable solution in estimating the area of photovoltaic panels on the roof. However, it was identified afterwards that this solution was not allowed due to energy calculation rules. One of the target goals was to evaluate the building regarding aesthetics, sustainability and cost. However, the BIM-modellers were unable to provide the expected insights with the tools; therefore, the specialists resorted to alternative "tools" of evaluation using their subjective assessment of sustainability. An overview of the observed outputs from the use of BIM-tools is listed in Table 3.

Discussion

A majority of the dilemmas and subsequent negotiations on how to solve them took place in the vicinity of the display of the 3D visualization. This proximity was necessary for the specialists, clients and users to interact with the BIM-modellers and the 3D models in order to convey their ideas and responses. This also meant that when dilemmas manifested themselves in the BIM-models participants acted spontaneously on those. This kind of interaction is also what Gero (1998) described as the design process as a sequence of situated acts. The use of the BIM-models to create not only 3D visualization but also 2D plans and sections allowed the participants to reflect and merge both their individual and social understanding of the building and align it with their motivations of what the building should be. These reflections were communicated to the BIM-modellers who responded through adaptations to the BIM-model. During the design process, non-alignments between the participants' motives for their design goals and what was visualized enforced renegotiations and resulted in new solutions.

The advantage of using BIM-based compared to non-BIM-tools for creating the building design was observed to both be the ability to re-use the information for other purposes, e.g. for BIM-analysis tools like Lumion or Vico Office. Moreover, it gave the BIM-modellers the ability to rapidly extract quantities of the design.

On several occasions, the participants required quantities that were used for decision-making such as crude cost estimations based on information from the BIM-model. Though informed by quantities gathered from the BIM-models, the participants often resorted to *satisficing* strategies, drawing on previously tried and tested solutions they knew from previous design projects.

In a study by Neff *et al*. (2010), it was argued that the explicitness of the BIM-model reduced the possibility of interpretative flexibility, which could constrain the creation of knowledge between specialists. They argued that the lack of information on paper drawings is an interpretive benefit because it allows each specialist to defer the rest of the information a specialization (e.g. structural engineering). Designers need a possibility for vague communication to keep some negotiations open and that BIM-tools lacking this possibility and this may ultimately lead to the poorer cross-disciplinary creation of knowledge. Our findings did not indicate that the explicitness of the BIM generated design model constrained the cross-disciplinary creation of knowledge. We found that the detailed and explicit representation of the design was coupled with the occurrences of dilemmas that the participants tried to address and this assisted them in developing the design. The explicitness of the design intents through the BIM-model created cross-boundary knowledge (e.g. space layout) Thereby, the results of the interviews are more related to the approach to organizing the use of BIM, rather than the technology itself.

A similar critique was put forward by Scheer (2014) who wrote that BIM-tools were limited in expressing the shape of the design because of an excessive focus on performance rather than design aesthetics. In our project, the architect interacted with the BIM modellers throughout the design process, jointly shaping the building design. Some of those interactions were managed and solved through the 3D models while other issues were solved using pen and paper to explain ideas that were then transformed digitally. This form of explicitness was observed to be a key benefit throughout the design process contrary to Scheer's (2014) arguments.

We observed that the participants aligned and compromised their work practices with the task at hand. When people want to work together successfully, they need to combine their dispersed objects of design (i.e. the different understandings and motivations of the design) into a shared object of design (Puonti, 2004). Bypassing some of the BIM-tool functionality was due to the architect resorting to practices she was familiar with. Puonti (2004) explained that when dispersed objects fuse together, they form new work practices and transform design. Since the participants had to address several dilemmas, they had to solve problems to secure the development of their design (Engeström 1991). It means that the development of the design product, the resulting work practices and the integration of BIM-tools were a result of socially created dilemmas.

This observation also echoes findings by Deken and Lauche's (2014) on collaborative innovation, who argued that objects (i.e. the design) emerge simultaneously with the formation of work practices. Because of the existence of dilemmas, new practices emerged that were at times improvisations to meet the demands of changing design.

The facilitators created rules how the BIM-tools were supposed to be used, but this was at times circumvented during the workshops. Davies & Harty's (2014) investigation on the implementation of BIM-tools at a building site revealed that efforts to extensively plan the use of BIM-tools were unsuccessful since it was highly affected by the emergent and dynamic conditions of the project. Both Ecotect and Vico Office were difficult to apply alongside the development of the BIM-model and to perform the analysis of the BIM-model certain information and consistency were needed. Our findings indicate a dilemma between the emergent nature of the design process and the need to comply with BIM-modelling rules. Non-compliance with the BIM-modelling rules leads to challenges in use, e.g. BIM-analysis tools to inform about design performance.

These findings are similar to Davies and Harty's (2013) investigation of how BIM-tools were used on site. Rules specifying the use of BIM-tools were prepared, but emergent needs during the process were prioritized. The emergent and changing needs are a fundamental trait of the processes in the construction industry and for the use of BIM-tools to be relevant they need to adapt to such changes better as experienced in both Davies and Harty's (2014) investigation and this. The setup, in this case, meant that the team had a limited timeframe in which they had to produce the building design. It determined the speed at which decisions had to be made including those to do with rule breaking to speed up the process.

Not being able to provide better insights, the specialists used satisficing in the decision-making process that led to a limited exploration of the space of possible solutions, leading to design flaws, e.g. like the event with the photovoltaic panels. These flaws add to Dorst's (1996) observation that designers still

Table 4. Overview of findings.

	Findings	Consequence for the design	Role
Theme 1	The 3D visualizations prompted participants to identify concerns or ideas which they pursued to solve.	Initiated discussions to improve the design of the building.	Assisting in mediating immediate visualization of emerging ideas.
	Point clouds were used with the BIM-model and enabled a 3D visualization of the design in the existing context.	Ensured alignment of the design with the building site and the inventory.	Acted as underlays in the BIM-authoring tool to further assist in identifying the potential dilemmas with the design and the site and inventory.
Theme 2	BIM mediated design resulted in developmental transformations of the building design process.	It ensured that the design progressed but at times it led to rule breaking.	The BIM authoring tool was used in a 'quick and dirty' approach to support design discussions immediately.
Theme 3	Discrepancy between the Ecotect processing of the results and the rules of estimating energy consumption in Denmark	The results were not used in the decision making.	The BIM-analytical tool was expected to support design decisions.
	Solutions were based on experience-based knowledge rather than insights based on results from BIM-analysis tools.	The optimization quality of suggested solutions was the same as projects without BIM.	BIM was used to analyze design aesthetics, but the results of Vico Office and Ecotect was not used in the decision making.

succumb to satisficing, and, in our case, they did so even when mediated by BIM-tools. Moreover, this reaffirms Kleinmuntz's (1985) observation that satisficing can cause inaccuracies and flaws, like the one observed with the solution related to photovoltaic panels that did not provide valid results that would work within a Danish context.

In this case study, we applied Activity Theory as our analytical lens because it allowed us to examine the object of an activity and any actions taken by people towards realizing its transformation (Engeström 2000). The use of Activity Theory allowed us to track motives, dilemmas and actions that led to changes in the object in design, thereby showcasing the holistic entities that constitute the activity of design, including individual, social and instrumental dynamics mediated by BIM-tools. The findings of our case-study are presented in Table 4 to indicate how the different functionalities of the BIM-tools either enabled or constrained aspects of the planned use.

The 3D visualizations allowed the individual participants to manifest their intentions, and this created at times dilemmas that the participants had to solve. Point clouds assisted in this process by providing a detailed representation of the building site and the inventory that would affect the design. This also shows how people's activities were driven by their motives. By transforming objects in their environments they were able to achieve their motives (Kaptelinin *et al.* 1999). We observed that during the development of the object (the building design), the people involved in the process faced many dilemmas. However, their desire to pursue the motive of their activity resulted in improvisations and at times rule breaking. Taking various actions in response, shaped the object of design, and the actions were either supported or constrained by using BIM-tools. Because of such improvisations, it was difficult to use BIM-analysis tools to inform the decision-making, which instead mainly relied upon satisficing.

Conclusion

The aim of this article was to show, analyze and discuss an investigation into the consequences of using BIM-tools in a collaborative building design setting consisting of different specialists. We presented a case study of an inter-organizational design process of a naval rescue station project in Denmark. The activities were observed and the data were analyzed using Activity Theory framework to explore the complex social practices when people with different expertise come together. Utilizing this framework allowed for the identification of dilemmas during the development of the design using BIM-tools. Dilemmas were identified as all the instances where an activity had to be interrupted and where the team had to negotiate their understandings in order to pursue their shared goal to finish the building design by coming up with new solutions. This approach helped us to examine the mediating role of the different tools they used in the design process activity and study how BIM-tools shaped the production of the object (the building design), and how it evolved at particular points in time. Utilizing Activity Theory for the analysis allowed us also not to be limited to an examination of technical capabilities but identify how different expertise and nested understandings shaped what people saw – or not – that BIM-tools afforded to the design process.

We found that BIM-tools played a central role in the development of this design since they created visualizations that drew different team members together to communicate issues they detected and how to overcome them. These responses were typically situated improvisations that were implemented at the moment to ensure the continued progress of the transformation of design. The BIM-modellers' primary motivation was to ensure the progression of the design development and not to optimize the use of BIM-tools and this meant that the improvisations caused inconsistencies in the BIM-models. These inconsistencies created difficulties in applying the BIM-analysis tools as intended to evaluate the performance of the suggested solutions and did not provide for an exploration of the space of possible solutions. However, the project concluded with a finished design even though it did not fully implement the available suite of BIM-tools as intended. Additionally, the building was built and was recently awarded a prize for its design (Skagen Byfond 2017).

Our study was limited to focusing on one experimental case, where only a few selected BIM-tools were applied within a limited timeframe. This Danish case study presented a situation where BIM-tools were used in a cooperative setting. However, it must be noted that this scenario does not represent necessarily a traditional where teams do not necessarily work together at the same time at the same physical location. The significance is that the case represents a uniquely orchestrated situation to examine the possibilities of collaborating with the help of some BIM-tools. Future research in this field may benefit from exploring our findings in different constellations and perhaps also in different cultural/country settings to expand the understanding of how BIM-tools may be applied in practice.

We suggest that future research should investigate how BIM-tools can be further developed and applied in building design practices to assist the designers in going beyond satisficing and extend the bounded rationale we humans are limited to. In this specific workshop setup, the participants used BIM-tools typically used in the Danish building industry, though potentially more flexible and rapid BIM-tools existed at that time.

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