Møller, N.L.H. and Bansler, J.P. (2017): Building Information Modeling: The Dream of Perfect Information. In: Proceedings of 15th European Conference on Computer-Supported Cooperative Work – Exploratory Papers, Reports of the European Society for Socially Embedded Technologies (ISSN 2510-2591), DOI: 10.18420/ecscw2017-24

Building Information Modeling: The Dream of Perfect Information

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Abstract. Over the past decade, Building Information Modeling (BIM) – an advanced modeling technology and associated set of processes to create, develop, and analyze digital building models – has emerged as one of the most promising approaches for improving the performance of building projects. It has been heralded as a 'digital revolution' and it is expected to improve collaboration, productivity, and product quality throughout the building life cycle by providing 'perfect information' on which to base the design and construction (Crotty 2012). However, little is known about the use of BIM in practice, and it has so far not been studied from a CSCW perspective. In this paper we present preliminary findings from a field study of a large hospital construction project in Denmark. The project is in its early phases, so the focus is on the role of BIM as a platform for collaboration among client, architects, engineers and future users regarding the *conceptual design*. Our findings suggest that recurrent reviews of the evolving digital model played a key role in the collaboration. We identified three kinds of design reviews: clash detection, scenario-based reviews and embodied reviews – each focusing on specific aspects of the conceptual design.

Introduction

The architecture, engineering and construction (AEC) industries are on the verge of a fundamental transformation towards digitized construction. This is, at least, the picture that emerges from the growing body of literature on Building Information Modeling (BIM). Its proponents often describe it as a digital revolution: "This is digitized construction; building with *perfect information*. This form of construction will be as different to today's analogue industry, as today's digital manufacturing and retail industries are different to their 1970s analogue predecessors" (Crotty 2012, p. xiii). There is broad agreement that BIM is "not just a technology change, but also a process change" (Eastman et al. 2011, p. vii).

Collaboration is at the core of BIM. It is seen as a means to overcome the fragmentation of the building process, which often causes unanticipated cost overruns, delays, and lawsuits, by providing a foundation for effective collaboration between the different actors involved from the early design phase through project handover to facility management. BIM is also expected to facilitate user participation in the building process, because "building models are far more communicative and informative to lay people than technical drawings" (Eastman et al. 2011, p. 363). BIM may, for instance, allow users to interactively review a building design in an immersive virtual environment such as a CAVE.

Meanwhile, little is known about the use of BIM in practice and the effects this has. Much of the existing literature on BIM can be characterized as having a promotional agenda, of a somewhat utopian quality (Miettinen & Paavola 2014). There are few in-depth empirical studies of the practical use of BIM technologies and processes in building projects and, despite the fact that collaboration takes center stage in the approach, BIM has not yet been studied from a CSCW perspective.

To begin to address this gap, this paper presents preliminary findings from an ongoing field study of the use of BIM in a hospital construction project in Denmark. The project is still in its early phases, so the focus here is on the role of BIM as a platform for collaboration amongst the client organization, architects, and future users around the conceptual design.

We found that recurrent *design reviews* of the evolving digital model were key to the process. We identified three different types of reviews: clash detection, scenario-based reviews and embodied reviews – each focusing on specific aspects of the conceptual design. While the first two types of reviews relied mainly on the digital building model, the embodied reviews allowed future users to experience the proposal 'for real,' for instance by exploring full-scale mock-ups or by participating in site-walks together with the architects.

The remainder of this paper is structured as follows: The next section briefly reviews prior CSCW research on architectural design; section 3 presents the concept of BIM and discusses the notion of parametric modeling; section 4 introduces the case; section 5 present our findings; and section 6 summarizes our conclusions and provides suggestions for future work.

Related work

There are relatively few studies of architecture and building construction within CSCW. However, although the CSCW literature on architectural work is not extensive, there are some important insights that may be derived from previous studies that we briefly present in the following section.

First, it is well documented that creating and interpreting representational artifacts are at the core of building design and construction. Modern building projects are notoriously complex and intensely collaborative, involving not only architects and engineers, but also building contractors, clients, user representatives, local government authorities, and other external stakeholders. To manage this complexity and diversity, architects and engineers rely on a bevy of representational artifacts ranging from informal and imaginative sketches, scale models and 3D visualizations intended to convey an idea or a concept to precise and very detailed CAD plans and technical drawings serving the needs of engineers and builders (Büscher et al. 1999, Christensen 2008, Harper & Carter 1994, Schmidt & Wagner 2005).

Second, as Schmidt and Wagner (2005) have pointed out, representational artifacts play a special role in architecture and building design for the simple reason that "architectural work is different from many other types of work insofar as the 'field of work' does not exist, that is, does not exist *objectively,* in advance, but is constructed in and through the process of design and planning and, ultimately, construction" (p. 363).

Third, representational artifacts have different affordances, and a recent study by Retelny and Hinds (2016) has documented that architects intentionally created different representations for different actors and purposes throughout a project. In some cases they even "duplicated effort by generating similar drawings for different audiences" in order to facilitate interactions with clients and contributors (p. 1320).

Fourth, it is important to understand that the various representations do not stand alone, but are highly interrelated. As the building project progresses, new representational artifacts are created, collated and interwoven to form a 'corpus' of 'texts,' which supports the collaborative work effort (Christensen 2015). The individual representations do not 'make sense' unless they are understood in association with other artifacts and their position in the 'taskscape,' that is, the ensemble of tasks that, taken together, constitute the project (Christensen 2008).

Finally, it should be noted that, except for the study by Retelny and Hinds (2016), much of the sparse CSCW literature on architectural work and building construction is based on empirical studies carried out a decade or more ago. Although theses studies provide valuable insights into the complex and collaborative nature of modern building projects, they do not reflect the profound changes underway in the architecture, engineering, and construction (AEC) industry driven primarily by digitization.

Building Information Modeling

Increased collaboration and better communication across organizational boundaries play a key role in the BIM rhetoric (Miettinen & Paavola 2014). According to

Eastman et al. (2011), the hope and expectation is that BIM will move the AEC industry "forward from current task automation of project and paper-centric processes" toward "an integrated and interoperable workflow where these tasks are collapsed into a coordinated and collaborative process that maximizes computing capabilities" (p. 17).

Eastman et al. (2011) emphasize that "BIM is not a thing or a type of software but a human activity that ultimately involves broad process changes in design, construction and facility management" (p. xi). More formally, they define it as "a modeling technology and associated set of processes to produce, communicate, and analyze building models" (p. 16). In this context a building model is a digital 3D representation using object-based parametric modeling to represent building components and their associated properties. According to the National Institute for Building Sciences (NIBS) in the U.S., the vision is to have an "information model for each facility, new or old, which *contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle*" (NIBS 2008, emphasis added).

The concept of parametric modeling – that is, the ability to construct building models by assembling and linking parametric 3D objects, which represent the physical components of the building, such as walls, windows, ducts, and pipes – is key to understanding BIM. A *parametric object* is a digital representation of a building component defined by rules and parameters that determine the geometric shape as well as nongeometric properties and features, e.g. relations to other objects, physical properties, price and delivery date. An object is always an instance of a class, where a class can be defined as a template or blueprint that describes the geometry, properties and behavior of a specific type or 'family' of things, e.g., slabs or beams (Eastman et al. 2011).

Objects (or properties) can be specified as being related to other objects (or properties). For instance, "it is possible to stipulate that a particular wall must be parallel to and a specified distance from another wall; that it is attached to a third wall at a particular angle, that it is perpendicular to the floor it rests on, and so on" (Crotty 2012, p. 84). Changes made to one object (or property) will therefore automatically be reflected in related objects (or properties). In this way, parametric modeling allows for "effective low-level automatic design editing" (Eastman et al. 2011, p. 39).

Another often claimed advantage of parametric modeling is that the 3D-model can be used to easily create design visualizations in various formats, and for various purposes. The expectation is that visual simulations can be used to elicit input from stakeholders unaccustomed to reading architectural drawings (Eastman et al. 2011, pp. 158-160).

BIM applications come with a set of predefined parametric object classes "meant to capture the standard conventions in the area of building that the application targets" (Eastman et al. 2011, p. 54). In addition, users can define their own parametric object classes, either by modifying a predefined class or by creating a new custom object class. Object classes can be defined at different levels of aggregation, so it is possible to model composite building components (e.g., an interior wall composed of a steel or wood frame, fiberglass insulation, and drywall).

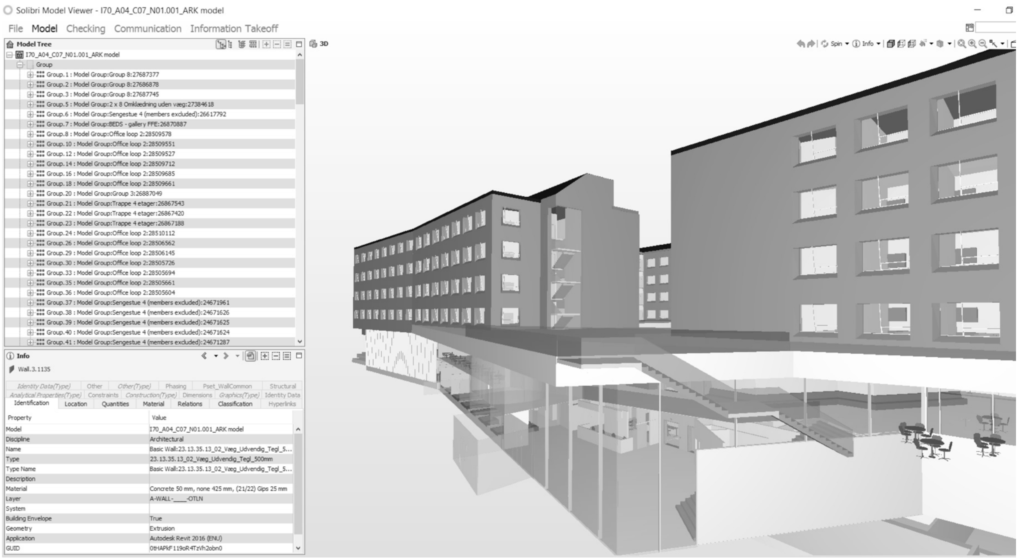

Figure 1. The digital building model: The model is interactive meaning that when marking an object, e.g., a door, specifications of the door appear from the database in the left side.

A multiplicity of models

This sounds great in theory, but in reality the vision of incorporating all relevant building information into one, unified model is not (yet) possible (Crotty 2012, Törmä 2013). Large construction projects involve numerous different specialists, such as architects, structural engineers, MEP (mechanical, electrical and plumbing) specialists, contractors and fabricators. Each group provide specialist input at different points in the design and construction process, and each group has its own discipline-specific BIM design tools and models. Therefore BIM-based projects will always involve multiple *partial*, but *interrelated* models which "represent the building from a particular perspective" (Törmä 2013, p. 412). In daily practice these discipline-specific models are often referred to as 'native models' (the architectural model, the structural model, the MEP model, etc.).

The fact that each group of specialists creates their own native model, more or less independently of all the others, opens up for gaps and inconsistencies – so-called 'clashes' or 'collisions' – in the design that need to be addressed. As a consequence, periodic design reviews and clash detection is an important and integral part of the BIM modeling process. In practice, this is often done by bringing the native models together at key points to create a single, complete 'reference' or 'master' model of the building, which will then be reviewed for omissions, clashes and other inconsistencies. Clash detection can in principle be performed 'automatically' using specialized design review software.

It should, however, be noted that this master model will only contain a *subset* of the data in the native models and that it can only be used in a *read-only* mode. Each of the discipline-specific design tools store its model in a proprietary data format, but can also export data in a standard format, typically IFC[1]. However, important information, particularly all parametric information, is lost in this process "since it cannot be represented in IFC" (Tölmä 2013, p. 414). This, of course, also means that any changes that need to be made after a review, for instance as a result of the identification of a 'clash,' must be done in the respective native models.

The case

We are studying a large hospital construction project, which aims at extending and refurbishing an existing general hospital located in Copenhagen, Denmark. The project involves the design and construction of a new main hospital building of 75,000 m^2 and the refurbishment of 12,000 m^2 of the existing buildings. The new hospital will serve approximately 450.000 citizens in the central part of the Capital Region of Denmark.

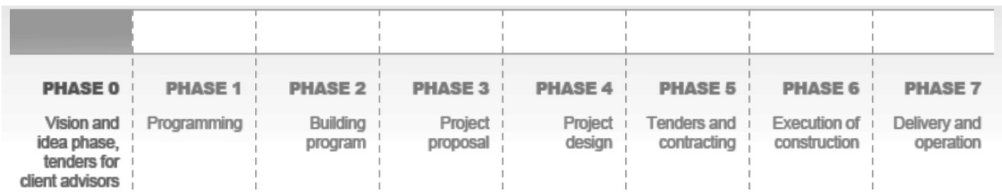

Figure 2. Project phases throughout the 'design-bid-build' process running from 2010-2025. The project is currently at the beginning of Phase 3 'Project Proposal'. (Accessed 08.02.2017 from Danishhospitalconstruction.com)

The building project started out in 2010 (see Figure 2) where the client advisors were appointed (Phase 0). Then followed a process of putting together the competition brief. The actual 'competition' of who would design and built the hospital was organized as a tender. The winning project was announced in the end of 2015, which was also the time where this study was initiated (Phase 1). The

[1] IFC stands for 'Industry Foundation Classes' and it is an open data standard developed by the BuildingSmart consortium (http://www.buildingsmart-tech.org).

study was conducted within the client organization with particular focus on the collaborative work around BIM amongst the user groups within this setup.

There are many project partners and they change in the course of the building project. There are, however, some partners engaged throughout the majority of project phases. These partners are 1) the client organization 2) the hospital 3) the project consortium (in Danish *Totalrådgiver* or *TR*) 4) consultants specialized in BIM, and 5) the client's advisor. These partners all represent larger organizations. Below is a brief description of each partner and their interdependence.

1) Client organization: The client organization consists of a mix of people with various professional backgrounds who collaborate in managing and reviewing the building project throughout the design and construction process. The professional composition of this group is changed in order to accomodate the competencies needed in the different phases of the project. At the beginning of the project emphasis is given to the conceptual design, whereas later it will be the tender process.

2) The hospital organization: Users (healthcare practitioners) play a crucial role in the initial design process by providing input as part of the conceptual design review. User participation was organized as a series of workshops, in which mostly nurses and doctors were invited to attend. Occasionally, other types of healthcare practitioners were invited. Different 'user groups' were formed to develop sub-concepts for 'day clinics', 'bed wards' and 'the ED' etc. The current hospital vice-president also heads the client organization (but formally the organizations are separate).

3) Project consortium: The consortium that won the tender process is a temporarily constituted group of firms, established solely for this tender. The project consortium consists of a Danish architectural firm and an American architectural firm, a Danish engineering firm and their sub-contractors, as well as a consultancy company specialized in hospital planning. The consortium is jointly and severally liable for project delivery, as stipulated in the contract that forms the basis for their collaboration on the design and construction of the future hospital.

4) Consultants specialized in BIM: The consultants are hired in to ensure compliance with technical requirements in terms of how to model in BIM. They are responsible for clash testing the BIM model throughout the process of design; relying on specialized software for clash detection. This also means that they define, for example 'clash rules'. The BIM consultants provide monthly reports of clash tests and create a prioritized list of collisions. Finally, the BIM consultants negotiate with the project consortium what are the important clashes to correct.

5) Client advisor: The client advisor is hired in to assist the client in developing the competition brief and continues to act as an independent advisor throughout the building project. The client advisor assists the client organization in reviewing the design in relation to, for example, sign-offs. The client advisor is considered to be a general advisor rather than a specialized one such as the BIM consultants that are hired in.

Data collection and data analysis

The Danish government has stipulated that from 2013 all public construction projects must use BIM (BEK no. 118 of 06/02/2013) and, accordingly, BIM has played a key role in the building project. BIM has been a clear priority from the beginning of the study, initiated in December 2015, at the same time the winning proposal was announced. Ethnographic studies were conducted (ongoing) and include 112 hours of observations on site.

The study is conducted in agreement with the client organization. Our prime focus is the design reviews that take place on-site, and/or with representatives of the client organization present. However, members of both the project consortium and client organization acted as our peers throughout the iterative process of collecting and analyzing data.

First, to collect data on BIM we began by mapping every time there was mention of or indication of a connection to BIM: We participated in sessions planned by the client organization where e.g. the managerial principles were outlined. We conducted informal interviews with consultants, architects and others working on the hospital project and collected various types of documents to understand, for example, the materiality and size of a BIM model. Eventually, the first digital building model was submitted as part of the design proposal (outline proposal) and we could follow how it evolved through 'sign-offs'.

Secondly, given our focus on the practices around the design reviews of the digital building model in between sign-offs, we decided to study and analyse the relationship between digital and physical representations. Based on our literature review, in which the advancements of BIM and the apparently omniscient possibilities of this type of digital building modelling are herealded, we were puzzled by the seeming importance of 1:1 scale mock-ups and site-walks, and so they serve as another focal point in our analysis that we turn to next.

Findings

A digital building model (BIM) does not come into existence 'out of nowhere'. It is developed after months and months of preparations where architects, advisors and the client organization negotiate the managerial principles, e.g. the appropriate level of detail in the BIM model and when deliveries (sign-offs) are required. At the same time, the *concept* for the future hospital has to be consolidated in the sense that decisions on main flows, size and functions have to be in place in order to begin the BIM modeling. Once these decisions are in place the project consortium begins work on collating the BIM model.

As previously mentioned the digital building model consists of a 'master model' and several native models, e.g. an architectural model, a structural model, a MEP model, etc. Thus, the various specialist groups (architects, structural engineers, MEP specialists, landscape architects, etc.) create and develop their own native models using discipline-specific authoring and analysis tools. The information links up to a room database that collects all information for each type of room in the model hospital. At regular intervals, the native models are integrated into the composite 'master model' using specialized aggregation software.

An architect from the project consortium explains the qualities of the 'master model' by making an analogy to a library.

> "Building Information Modeling is like a library due to the amount of knowledge that can be kept and leveraged about a project. Each user (architects, engineers etc.) can see the full library and contribute by 'checking out' different books. By this I mean that when we add something or change something in our local files we literally have that knowledge to ourselves. Then, when we save our local file back to the central file, we give that knowledge back to the library by checking in our books. That's where the magic happens, previously the other systems would not let two people access the same information. So, two people could not be in the same level 2 floorplan), but now 10 people can be in the same floorplan and making changes. People can be making changes in their local [native] model at the same time and they can actually save [these changes] to the central [master] model at the same time. The software [Revit] will pick who goes first as a part of their full save to central. It also updates all of the other content that has changed from other people's saves. This way we are all sharing the same information, because although we have our own copies they are always tied to the master/central file"
>
> (*In situ* interview with architect 07.04.2016 *and* 09.02.2017).

What the architect points out here is one of BIM's important qualities, namely that it allows for *synchronous* work by several different people at a time. Working in parallel is, however, not without its problems.

A common flaw in a digital building model is, for example, 'double modeling' (Exigo 2017). This flaw is typically provoked by simple mistakes, for instance, a new deck is added but the 'old' one is not erased from the digital building model. The architect explains:

> "The double modeling, typically happens when [there is a] misunderstanding [as to] who really owns it [e.g. the deck]. In the example of the floors, the architect owns the floor finish (i.e., tile, wood etc.) but engineering really owns the structural concrete. In terms of who gets into BIM first, there has to be different stages of that floor. So in the beginning, we [architects] might not know how large or how deep, but we know we need a floor. The Architectural team will put in a predesigned/ typical floor for reference until we give that element to the Engineering team where they will put the pans and joists and design in - and we, the Architectural team, get more comments and feedback from the

client to understand flooring finish. It is all a dance between both designers, client and users".

(Architect elaborating on *in situ* interview 21.04.2017).

The organizational setup around the 'master model' ensures, in principle, that work is coordinated at all times; even though it is clearly still important, as the example of double modeling illustrates, to review every aspect changed or added in the BIM model. Hence, 'reviewing' is essential for BIM modelling to be effective and so we turn our attention to practices concerning design review or 'testing'.

Reviewing the digital building model

We have identified three different types of reviews in the initial process of conceptual design that are essential to practitioners' collaborative use of BIM: 1) clash detection 2) scenario-based reviews, and 3) embodied reviews.

Clash detection (automated): As the digital building model is being created it consists of several discipline-specific native models, for example, an architectural model, a structural model, an MEP model etc. – that together come to form a 'master model'. The master model is submitted to clash detection testing approximately once a month (*In situ* interview with project leader 09.02.2017) to make sure that the native models do not clash. BIM consultants conduct the clash detection by applying specific analysis software (e.g. Solibri). The results of the clash detection test are then discussed with the project consortium, based on a prioritized list of clashes. It makes a huge difference what the rules of clash detection are: One example of a 'clash rule' identified in the project is that surfaces of walls should stop 10 cm. above the floor (*in situ* interview with project leader 09.02.2017). To be able to effectively clean and wash the floors in the future hospital, the floor material continues 10 cm. up the wall. This clash rule resulted in almost 5000 clashes (counted as the number of rooms where the flaw was detected). This is, however, considered as a non-important clash, because it is commonly known amongst the professionals that the painters would never paint those 10 cm. of floor material. What this example also illustrates is how the clash detection test is not strictly automated but based on a collaborative practice of deciding what are the important clashes that need to be corrected. Decisions on which clashes are the most crucial take time; time during which the design continues to be changed in the BIM model. Thus, another dilemma with clash detection is that the entire process around negotiating the importance of test results is sometimes slower than changes made in the master model. To avoid clash detection becoming redundant, it is crucial that BIM consultants and the project consortium agree on what is a reasonable level of 'testing' in terms of clash rules and on the results that follows from the automated tests.

Scenario-based reviews: Another aspect that we identified in the study as being important for how the BIM model is recursively checked, is reviews for omissions related to *functionality*. To check for omissions and functional design flaws likely to only be discovered by practitioners working in the hospital, scenario-based reviews are conducted: For example, one design flaw identified by a user group focusing on the standard patient room was that the bathroom 'space' seemed too small (*In situ* interview 15.08.2016). User groups were organized around 3 workshops to inform the conceptual design on different topics, for example, the standard patient room (and associated private bathroom). The client organization ran the workshops where project architects and the client advisor also participated in facilitating reviews of the conceptual design. A projector and prints of 2D-floorplans were provided in all 3 workshops to help focus the discussions (BIM allows for both 2D and 3D visualizations). Thus, architects were able to manipulate the design in this case of the standard patient room 'live' using the projector and guided by the users' input. The observation in the first workshop – that the bathrooms seemed to be too small – was supported by formal guidelines[2], one of the project leaders of the client organization noticed. Taking decisions on, for example, the size of a bathroom is something that has significant consequences for costs when more than 600 standard patient rooms (and bathrooms) are to be built. Therefore, the outline of the standard patient room was 'taped' on the floor in the second workshop. As a result of the discussions at this workshop, the size of the bathroom was adjusted prior to the third workshop with users; even though further exploration of the conceptual design with a planned 1:1 scale mock-up of the patient room was still needed.

Embodied reviewing: 'Testing' or reviewing digital building models involves more than detecting 'clashes' and teasing out omissions and functional design flaws. Another important aspect in making BIM effective in practice, is the users' 'unfiltered interaction' with design. The notion of 'unfiltered interaction' is an empirical category that emerged in a process consultant's description of the difference between reviews of 2D floorplans with users and reviews that take place in the actual context of the 'hospital'. By 'unfiltered' the process consultant wanted to highlight how users interact differently with a mock-up when considering the use scenario *vis-à-vis* simply interacting by 'using' a space (*In situ* interview with process consultant 30.01.2017). Thus, according to the process consultant, the 'unfiltered interaction' with a mock-up lead to different types of reflections. There is a difference, the process consultant explains, when hospital practitioners sit in, for example, a couch in a 1:1 mock-up rather than just thinking about how they would probably sit in the couch. The input is richer compared with the input that users provide when interacting with, for example, the 2D-floorplans in the user groups or even when interacting with a mock-up 'taped' on the floor (*In situ*

[2] Capital Region of Denmark 2011

interview with process consultant 30.01.2017). Drawing on Dourish' (1999) notion of *embodied interaction*, we call this type of testing 'embodied reviewing'. Embodied interaction, according to Dourish, describes "*both a physical presence in the world and a social embedding in a web of practices and purposes*" (1999 p. 1). Taking the importance of 'embodied reviewing' seriously, in the following section we take a closer look at the use of physical representations such as mock-ups and site-walks in order to deepen our understanding of how BIM is made efficient in practice – and we also consider the qualities of these artifacts.

The role of embodied reviews

What does it mean in practice to carry out an 'embodied review' of an architectural design and what role does it play in relation to the digital building model? What are the different representations involved in 'unfiltered' embodied reviewing? And what are the qualities of these representations that make embodied interaction or testing different from direct interaction with the BIM model? The following section explores two specific examples of embodied reviews, namely 1) a carefully planned *site-walk, guided by sticks* to simulate the layout of the future Emergency Department (ED), and 2) a *mock-up* of a standard patient room built within the existing hospital's medical department.

Site-walk: Comprehending the *size* of a 'space' is not straightforward. Even people who have worked in AEC for years are sometimes puzzled by size issues. The challenge is how to realize in advance what it means to work in a space of a particular size. The users – the hospital practitioners – were not used to 'reading' 2D and 3D floorplans and translating size into something with which they were familiar. This also raises the question of what it means to review a design with users. This is exactly the point of learning people how to interpret digitized representations.

The users' understanding of size evolves together with the project: Similar to architects that rely on certain rules of thumb, such as 'space' being estimated from the number of ceiling tiles, users also have to learn about the size of a 'space' in a way that makes sense from their perspective (*In situ* interview with process consultant 02.02.2017). To assist users in developing their sense of 'space', a site-walk with users was organized as part of reviewing the conceptual design of the ED. The concept of the ED in the new hospital will be significantly different from the existing. It will be the main space where patients are admitted to the hospital. Patients are expected to spend up to 48 hours in the ED in the future.

Through simple measures, including the positioning of sticks labeled with the names of particular ‘spaces’ in the future ED (triage, treatment rooms and trauma), a senior architect and process consultant marked out the exact size of the future ED and how the various functions would be situated. Hospital practitioners (nurses and doctors primarily) were invited for a tour in the future ED to reflect on the layout of the future department and what it would mean if the department was located on a single floor rather than on two floors. Walking through the future ED the hospital practitioners, for example, counted the *number* of patient treatment rooms they imagined passing.

Figure 3. Mock-up of the future ED to evolve users’ sense of ‘space’ and the conceptual differences in the layout if ‘stacked’ horizontally vis-à-vis planned in a straight line vertically.

The site-walk provoked a number of issues and questions, e.g. the doctors imagined that it would be difficult to pass through the different zones of the ED without being stopped on their way to, e.g. trauma. Moreover, this example illustrates how learning about the size of a space by interpreting floorplans and the *embodied interaction* with a particular space are very different phenomena. The site-walk allowed hospital practitioners to connect the familiar experience of walking and the floorplan of the future ED to explore issues of space and size.

Mock-up: In the case of the 1:1 scale mock-up of a standard patient room, the interest was also mainly to review the conceptual design in the digital building model. The final layout will be copied more than 600 times in the future hospital, making this one of the most important rooms to review as even the smallest change will have significant effects when scaled up to the entire hospital.

The mock-up of the patient room was initiated at the same time as the digital building model, and ran in parallel. Thus, the mock-up and the BIM model are closely related as illustrated in the example of bathroom design. When the users found that the bathroom was too small during the scenario-based workshops, the mock-up became an important alternative means for reviewing this space.

Figure 4. First version of the mock-up of standard patient bathroom that will become a fully functional patient room for 'embodied reviewing.'

This simple, rough 1:1 scale mock-up in plywood allowed hospital practitioners to experience and explore the bathroom 'for real', and this gave more credibility to the conclusions reached at the previous workshops with users. In the 'taped' version of the room on the floor, users had to think about where the walls would be. In contrast, the 1:1 scale mock-up allowed users to step into the bathroom without thinking about how the walls were represented. This is what we suggest conceptualizing as 'embodied reviewing'.

Discussion and conclusion

There is no doubt that BIM is an important technological innovation that will be driving fundamental changes in the AEC industries over the next decades. It is, however, not yet possible to project exactly how these changes will play out in practice.

The vision of BIM is to improve collaboration and coordination amongst the many different parties involved in large construction projects by replacing the plethora of traditional representational artifacts such as floor plans, section views, detail drawings and scale models (Christensen 2008, Schmidt & Wagner 2005), with a single, unified digital model, which "contains all appropriate information created or gathered about [the building] in a format useable by all throughout its lifecycle" (NIBS 2008). However, even the most optimistic proponents of BIM have realized that this is hardly possible in practice due to both technical constraints as well as to the many different stakeholders' specialized information needs (Retelny and Hinds 2016, Törmä 2013). For the moment, it is generally accepted that instead of a single unitary model, the building information model "is more likely to take the form of a federation of separate, but interconnected, discipline-specific sub-models" (Crotty 2012, p. 81).

Against this backdrop, we set out to explore how BIM is implemented in practice by studying the creation and use of a (federated) building information model in the early phases of a large hospital construction project. We found that the model played a key role in the development of the new hospital building's concept design, but also that the integration of the input from the various specialists into a coherent 'master model' proved to be more complex and challenging than one would expect from the literature. According to one of the architects this process works out best, "when the design team and the client can *make designs as early as possible and try not to change them"* (Architect elaborating on *in situ* interview 21.04.2017, *emphasis added*).

More specifically, we discovered that recurrent *design reviews* played a key role in facilitating collaboration amongst the architects, engineers, and user representatives involved in the development of the model. We identified and examined three different types of reviews in use in this project, namely (1) reviews based on automatic clash detection, (2) scenario-based reviews with users, and (3) reviews involving users' embodied interaction with physical mock-ups and spaces. The first type of review focused on detecting *clashes* between the native models produced by different specialist groups; the second type of review focused on identifying omissions and *functional* design flaws as seen from the perspective of future users; and the third type of reviews focused on exploring aspects of the users' *embodied* experience when navigating the design space.

There are two important points worth highlighting about these reviews. First, the so-called 'automatic' clash detection (Eastman et al 2011, p. 272-3) seems to be not-so-automatic after all. BIM-based clash detection is no doubt easier, faster and more reliable than the traditional approach of overlaying 2D drawings (or 2D CAD layers) and visually identify potential conflicts, but it nonetheless requires the specialist groups' concerted effort and collaboration. They have to agree on what aspects of the design to focus on, and they have to define appropriate clash rules before running the clash detection software. If used without first defining precise and relevant search criteria, the software will identity tens of thousands of clashes; the importance and relevance of which need to be assessed (depending on the project stage and task at hand). Given the importance of clash detection for large building projects, an obvious area for further research would be detailed, qualitative investigations of the tools, techniques and practices of BIM-based clash detection.

Second, it is interesting, and seen from a BIM perspective perhaps surprising, that the client organization found it necessary to conduct what we, inspired by Dourish, refer to as 'embodied reviews,' as a complement to clash detection and scenario-based reviews. It is interesting, because the BIM literature suggests that digital building models will make the use of traditional scale models and physical mock-ups superfluous. This is because digital building models "are far more flexible, immediate, and informative than computer-renderings of buildings produced using CAD technologies" (Eastman et al. 2011, p. 362). Furthermore, they allow for the creation and testing of virtual mock-ups in immersive VR environments. Such virtual mock-ups or VR models are supposed to offer the same advantages for user feedback as physical mock-ups and, in addition, be much faster and cheaper to create and, perhaps in particular, to modify. However, whether these optimistic claims can be substantiated in practice remains very much an open question (Leicht et al. 2010).

Seen from a CSCW perspective it is, we would argue, less surprising that the digital building model cannot stand on its own. Previous studies have shown that architects and building engineers rather than using a single uniform representation employ a vast range of representational artifacts, each of which is specialized for a particular purpose and audience (Christensen 2008, Christensen 2015, Retelny & Hinds 2016, Schmidt & Wagner 2005). The reason for this is, of course, that "representations are not the real thing (…); they are always fundamentally 'underspecified' with respect to that which is represented" (Schmidt & Wagner 2005, p. 364). In other words, every representation emphasizes a set of properties while ignoring others. Seen in this light, it is not so surprising that site walks and full-scale mockups can be useful as supplements to digital representations, because their 'physicality' accentuates other aspects of the proposed design such as the experience of space and size.

The hospital project, we are studying, has so far chosen not to invest in VR technology, but they are in the next phase of the project considering testing the use of desktop VR and immersive VR models to validate conceptual design and obtain user feedback. This will give us the opportunity to more fully explore issues of representation, embodied interaction, and spatiality by comparing and contrasting the performance of physical and virtual mock-ups. Thus, it will be interesting to explore if VR models can support 'user testing' of proposed building and room designs related to, e.g., work processes and patient safety. These are issues of practical concern as well as theoretical importance for understanding architectural design and construction from a CSCW perspective.

Acknowledgments

We are indebted to people working in the New Hospital Bispebjerg and in particular we wish to thank Behdad Bakhshaie, Hilde Schroll Jespersen, Sara Shumbera, Per Sams, Kristian N. Kiørboe, Louise M. Kofoed and Karen Grønkjær Kjeldsen for providing valuable support. We also wish to thank people working in New North Zealand Hospital (our 'sister' study) who played an important role in helping us understand the issue of study across sites. In particular, we wish to thank Sune From, Henrik Schmidt, Mette Stokholm, Karina Skog Nielsen, Rasmus A. Bang and Louise Lykke. This research was supported by the Velux Foundations award number 33295 and conducted as part of the Computational Artifact research project.

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