Affordances of Building Information Modeling in Construction: A Sequential Analysis

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Abstract

Introducing Building Information Modeling (BIM) systems in construction workplaces requires changes to well-established design routines and practices. This paper analyzes BIM-based design activities in a contemporary construction project in order to identify how design professionals have adjusted their practices and what users can accomplish with the new technology. Based on interviews with members from different design professions, a sequential analysis technique was applied to study design routines based on BIM artifacts. The findings indicate that BIM's cooperative affordances, such as its embedded work sharing functionality, were not enacted in practice. Moreover, the systems used did not provide support functionality to inform users in which context the production and coordination technology should be applied. In addition, infrastructure functionality allowing users to transfer knowledge, skills or methods to other projects or planning situations could not be identified. Last, the systems applied in our case did not afford users to store or house information within a device. We found that actors at early project stages had a greater degree of freedom when it came to making use of their design tool affordances than actors working at later project stages. Thus, we argue for the need to focus managerial attention at the choice of design technologies and the enactment of affordances at early project stages. Our findings illustrate weaknesses in existing practice and highlight possible improvements.

Keywords: affordances, sequential analysis, digital design, inter-organizational collaboration, building information modeling

1. Introduction

In recent years, the construction industry has embraced the use of information and communication technology (ICT) in its operations. Construction firms adopt technological innovations because they seek competitive advantage, want to resolve process related problems, are forced by their external environment to implement new technologies, or seek to improve collaboration and knowledge exchange with others (Bossink, 2004). Virtual modeling technologies, frequently referred to as Building Information Modeling (BIM), constitute core technologies for improving the process of construction. Examples of these technologies include applications for surface and solid geometry modeling, model-based drawing generation, 3D visualization, 3D animation and 3D schematic design. Anticipated benefits of BIM include performance gains, increased clarity in information sharing and

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reduction of errors in construction design (Baxter and Berente, 2010). Motivated by these prospective benefits many design offices have replaced their traditional two-dimensional design systems by BIM technology (Rivard, 2004). However, despite an increasing uptake of BIM, scholars report that the industry still misses out on many crucial advantages the technology has to offer (Ahmad and Sein, 2008, Neff et al., 2010). The industry focus on enhancing existing processes rather than changing the way of doing business hinders them from taking advantage of BIM technology. In this respect, construction professionals would need to improve the management of ICT and use technological innovations such as BIM as strategic organizational assets (Ahmad and Sein, 2008). A recent literature review recommended further research into the relationship of BIM's functional affordance and its human agency (Merschbrock and Munkvold, 2012). Functional affordances are defined as "the possibilities for goal-oriented action afforded to specified user groups by technical objects" (Markus and Silver, 2008, p.622). White (2011) argues for the need to conduct further theoretical and empirical work to understand digital infrastructure in practice by focusing on how different professions structure their interaction with the integrated software. Our research follows up on these calls by exploring how BIM is currently used and what BIM technology affords its users in construction projects. Based on our findings we identify areas in need for managerial attention. Thus, our research is guided by the following question: *How can we explore BIM's current use and affordances in construction design, to identify challenges and suggest improvements?*

To address this question we present the results of a case study conducted of a building construction project in Norway. To analyze our data we conduct a sequential analysis (Gaskin et al., 2010) of the design activities in the project. Based on this analysis we develop an understanding of the areas in need for further managerial attention. The intended contribution of this paper is twofold: First, we argue that research based on a sequential analysis can broaden the theoretical understanding of activities and their variations in digital construction design. Second, the practical contribution of the study is to showcase how sequential analysis can be of use to identify required changes to ICT management useful to improve current design practice. The organization of the paper is as follows: Section two presents the sequential analysis perspective, section three presents the research methodology, section four presents the data analysis, followed by the discussion and conclusion.

2. Analytical Perspective

The study reported in this article can be positioned within the current research stream on BIM's impact on social and organizational practices in construction projects (e.g., Gal et al., 2008, Harty and Whyte, 2010, Whyte and Lobo, 2010). This work reports persistent challenges to the successful deployment of BIM rooted in the industry and its established way of working (the projects' mode of organizing, contracts, fees and delays, etc.). Our study is based on the perspective of sequential analysis. Sequential analysis can be defined as an effort in which sequences of human activity, such as work processes are analyzed using time series (Gaskin et al., 2010). Sequential analysis is an analytical perspective widely used in disciplines such as engineering, economics and medicine (Lai, 2001). Further, this perspective has been deployed to analyze sequences of human activity in urban transportation (Wilson, 2001). Sequential analysis has also received attention by researchers interested in understanding routines and activity in digital design (Gaskin et al., 2010). Sequential analysis is a fruitful lens to identify variations and compositions of routines in design. For example, Gaskin et al. (2011) studied and compared digital design routines across several industries, i.e. a car manufacturer, a semiconductor manufacturer, a mechanical, engineering and plumbing contractor (MEP) and a manufacturing company producing hoses. They found that organizational context has an effect on digital design routines and their variation. Gaskin et al. (2010) suggested a specific methodology for encoding and analyzing routine composition in digital design, based on three steps: (1) determine sample and collect field data; (2) encode data into a lexical model of routine which serves as *"…an 'alphabet' to characterize elements of each design task*" (ibid. p.3); (3) analyze data. Thus far, Gaskin's work draws from a rather limited empirical base and he recommends researchers to analyze design practice in further contexts.

Gaskin et al. (2010) suggest a lexical model consisting of five key elements useful to encode design routines in project based organizations. These elements are: "**activities** [which] are comprised of **actors** engaged with **tools** that **afford** those actors the opportunity to produce design **objects**" (ibid, p.2). Gaskin et al. here adopt Markus and Silver's (2008) definition of functional affordance, as presented in section 1. An overview of the lexical model is presented in Table 1.

Table 1: Lexical model of design routines (adopted from Gaskin et al., 2010)

Routine element	**Definition**
Activities	Specific design task undertaken by actors
Actors	Individual or organization performing the task in question
Tools	Digital or physical tool used to perform an activity
Affordances (1-8):	Defines what an actor can perform with the tools used
(1) representation	functionality enabling users to define or change a description of a design object
(2) analysis	functionality enabling users to explore, simulate, or evaluate alternate representations or models of objects
(3) transformation	functionality to execute a significant planning or design task
(4) control	functionality enabling the user to plan for or enforce rules, priorities or policies governing or restricting the design process
(5) cooperative	enables users to exchange information with others
(6) support	functionality to inform users in which context production and coordination technology will be applied
(7) infrastructure	functionality to transport knowledge, skills or methods to other projects or planning situations
(8) store	functionality allowing information to be housed within a device
Object	The digital or physical outcome of the design activity

Gaskin et al. (2010) developed their view on affordances including eight sub categories based on typologies reported in literature (e.g. Leonardi and Barley, 2008; Henderson and Cooprider, 1994), except for the 'store' affordance which they introduced themselves. Gaskin et al. (2010) argue that their framework is limited in that it's "*more concerned with composition of design routines then their exact sequence* (p. 6)". We address this challenge by classifying the identified routines based on a sequential typology for construction design activities proposed by Evuomwan and Anumba (1998). The eight affordances proposed by Gaskin et al. (2010) are considered a good fit to address the research aim of our study, as they are designed to describe the different ways in which digital design tools such as BIM are applied by industry actors.

3. Methodology

The case study methodology was deployed since it allows the investigation of *"…sticky, practice based problems where the experiences of the actors are important and the context of action is critical*" (Benbasat et al., 1987, p.370). The case project was selected based on three criteria 1) the project participants had to resemble a typical project constellation in the industry (clients, architects, engineers, contractors); 2) the design had to be completed at the time of data collection; 3) BIM technology had to be deployed to some extent in construction design. The setting of our case study is the design and construction of a library and cultural center in southern Norway. The project comprises the construction of a library including a café, meeting places and administrative areas. The building's gross floor area is 1938 m2. The building's wooden structure consists of 27 ribs made of prefabricated glue-laminated timber elements and computer numerical control (CNC) cut plywood boards. In the period from April to May 2012, we conducted nine semi-structured interviews with professionals involved in the design and construction of the project. Semi-structured interviews were chosen as means for data collection as they allow for understanding the experiences from various practitioners using modeling technology in their daily work practice. Three of the interviews were conducted via Skype due to the firms' geographical locations in distant regions of Norway, while the rest of the interviews were conducted face-to-face at the companies. Each interview lasted for about one hour. The interview strategy chosen allowed us to capture the whole design interaction in depth. The interviewees had the following professional roles: design manager (engineering); structural engineer; electrical engineer; fire-protection designer; massive-wood builder (project manager); glue-lime builder (project manager); client's representative (municipality); architect and general contractor (project manager). The author's civil engineering background comprising both university level education and work experience helped to minimize potential social dissonance between interviewer and respondents. The interviews were recorded, transcribed and coded in NVivo 9™ in order to identify activities, actors, tools, affordances and design objects comprising the design routines under study (Table 1).

4. Analysis

The analysis in this paper is guided by the lexical model introduced in Table 1. We present our aggregated data on the case project's design routines and discuss how these were composed. An overview of our findings is presented in Table 2. The routines presented in Table 2 and in the following paragraphs are arranged in a temporal sequence taking into account their occurrences in the process chain. The proposed sequential stages are defined based on Evbuomwan and Anumba's (1998) typology:

- *Negotiation*: client requirements processing; preliminary conceptual design; design of schematics
- *Generation*: analysis and detailed design; design documentation
- *Execution*: construction planning

Routines labeled as 'negotiation' took place at initial project stages, activities labeled 'generation' took place in the mid-stages, and all activities labeled with 'execution' took place in the late stages of the project's design.

Table 2: BIM design routines in the Library Case

Activity	Actor	Tool	Affordance	Object
Negotiation Early-stage design	Architect Client	Architectural BIM software	Transformation Representation Cooperative*	3D BIM model 2D paper drawing set
		Sketching software	Transformation Representation	3D “snapshots” taken of the BIM model
		Rendering software	Transformation Representation	3D “photo realistic” rendered surface model
Generation Architectural design	Architect	Architectural BIM software	Transformation Representation Cooperative*	3D architectural BIM model 3D open standard IFC model 2D paper drawings
		Model viewer software	Cooperative	View of 3D open IFC files
Generation Structural design	Structural Engineer	Structural BIM software	Transformation Representation Cooperative*	3D structural BIM model 3D open standard IFC model 2D paper drawings
		Structural calculation software	Analysis	Structural strength simulations
		Model viewer software	Cooperative	View of 3D open IFC files
		Model checker software	Control	Combination of 3D open IFC files for clash detection
Generation Fire-protection design	Fire-protection engineer	2D CAD software	Transformation Representation	2D paper drawing set
		Computational Fluid Dynamics (CFD) software	Analysis	Fire growth simulation
Generation HVAC design	HVAC designer	Mechanical engineering BIM software	Transformation Representation	3D HVAC BIM model 3D open IFC model 2D paper drawings
Generation Electrical design	Electrical engineer	Electrical engineering BIM software	Transformation Representation Cooperative*	3D electrical BIM model 3D open IFC model 2D paper drawings
		Electrical dimensioning software	Analysis	Electrical dimensioning simulation
Execution Workshop design	Glue lime manufacturer	2D CAD software	Transformation Representation Cooperative	2D paper shop drawings (glue-lime beams)
		3D CAD / CAM solution for timber building	Cooperative	View of full-fledged 3D files
Execution Workshop design	Massive wood manufacturer	3D CAD / CAM solution for timber building	Transformation Representation Cooperative	2D shop drawings Bill of materials Computer Numerical Control (CNC)-data View of full-fledged 3D files
Execution Assembly planning	General contractor	2D CAD software	Transformation Representation Cooperative	2D Site-layout drawings 2D assembly drawings
		Model viewer software	Cooperative	View of 3D open IFC files
*functional affordance has not been enacted				

Early-stage design (Negotiation) was the first in a sequence of activities undertaken to accomplish the design. In close collaboration with the client, the architect developed an understanding of what the future building should be like. The architect visualized his ideas and presented them in digital and physical models, drawings and sketches. The digital design tools used in this routine were architectural BIM software, sketching software and rendering software. The architectural BIM software had the functional affordance to *transform, represent* and *cooperate* based on virtual BIM models. The architect used BIM software to develop the building’s outer shape and the building’s conceptual layout, thus, he made use of BIM’s transformational affordance. Further, he deployed the system to represent his design ideas in form of 3D models and 2D paper drawings to the client. The 3D models, projected on a screen, served as a basis for discussion at meetings and the 2D paper drawings were handed over to the client. The architect did not deploy BIM's embedded *cooperative* "work sharing" functionality at this stage of the project. The second ICT tool deployed in early stage design was sketching software. This software served as a complimentary tool to the main BIM system in that it allowed the architect to quickly create "snapshots" and sketches depicting certain details of the building, thus it's transformational and representational affordances were enacted in practice. In addition, the architect deployed advanced rendering software to create "photo-realistic" surface models of the building. The surface models made it possible for the architect to create 3D geometric elements signifying the "skin" of the building. Thus, the architect created several different architectural models by using three digital modeling applications in early design.

Architectural design (Generation) was the next activity studied. The main ICT tools deployed by the architect to develop the detailed architectural design were architectural BIM software and Model viewer software. The BIM software served as a tool to create 3D architectural models and at the same time to produce 2D paper drawing sets ergo BIM's *transformational* affordance to create a significant planning task and its *representational* affordance to define design objects were enacted. In addition, the software was used to create open standard IFC files of the architectural model which were used to exchange modeling data with other project partners. The model viewer software provided a *cooperative* affordance, serving as a common environment in which the IFC files created by other designers could be viewed.

We continue by discussing four engineering design activities namely: **Structural, Fire-protection, HVAC and Electrical design (Generation)**. The reason for discussing these activities together is that all these engineering services were provided by the same firm. In terms of sequence all of these activities took place concurrently. First of all, we found that the structural, electrical and fire protection engineers all used engineering systems having *analytical* affordances alongside with their main design systems. These were: structural calculation, Computational Fluid Dynamics (CFD) and electrical dimensioning software. These systems allowed for several analytical operations such as to simulate fire growth, calculate structural stability and electrical dimensions. With the exception of the fire protection designer, all engineers deployed BIM modeling systems to create 3D virtual models and 2D paper drawings of their designs, thus enacting BIM's *transformational* and *representational* affordances. These BIM systems were domain specific, e.g. for mechanical, structural or electrical design, and differed for instance by the availability of certain parametric objects (e.g. electrical designers require cable-trusses and structural engineers require parametric objects signifying reinforcement bars). The fire-protection engineer, however, created his design by using a 2D CAD system to generate 2D paper drawings of his design. The engineers made their designs match by simply discussing relevant issues in their office, for instance, the HVAC and electrical designers shared office and all other designers had their offices on the same floor in the same building. Thus, they did not use the *collaborative* functionality embedded in their BIM systems. However, the engineers had a system in place to align their designs with external parties such as the architect. This system consisted of a model viewer and a model checker, which allowed assembling individually created domain specific BIM models based on open standard IFC files into a common building model, thus this system was used for its *cooperative* affordance. Throughout the design stages they met with the architect and client in bi-weekly meetings in which all designs were matched and discussed based on a shared IFC model. The engineers and the architect together conducted virtual “walkthroughs” to detect clashes and conflicts between their models in building design.

The activities related to the **Workshop design (Execution)** took place after the architectural and engineering designs were more or less finalized. These activities included the creation of detailed workshop designs required for manufacturing of the wooden building components as well as the detailed planning of their on-site assembly. These services were provided by a general contractor, a massive wood manufacturer and a glue-laminated timber beam manufacturer. The general contractor had a mediating role in that he gathered design information provided by the architect and the engineers and distributed this information further to the massive-wood and the glue-lime beam manufacturer. The general contractor used a 2D CAD system to execute his design tasks ergo he made use of its *transformational* and *representational* affordance. The design objects distributed further were 2D CAD files and 2D paper drawings. In addition he deployed a 3D model viewer affording him the opportunity for “one way” *cooperation* where he could view models created by others but not share any models since no such were created. The general contractor used the model viewer application to view IFC files provided by the structural engineer and the architect as an information source for their on-site assembly crews. The glue-lime manufacturer used a 2D CAD application to create their shop drawings based on 2D drawings provided by the general contractor, thus they made use of 2D CAD’s *transformational, representational* and *cooperative* affordances. Alongside their 2D CAD system they deployed a 3D Computer Aided Design and Manufacturing CAD/CAM solution for wood design to view the architectural 3D model in order to understand the complicated roof shape of the building, thus utilizing this system’s *cooperative* affordance. They opted for using 2D CAD instead of their 3D CAD/CAM solution in design due to the fact that they did not have CNC production machinery large enough to produce the components required for the library. The massive wood contractor deployed an end to end 3D CAD/CAM solution to create their workshop design. The outcomes of their design activity were 2D shop drawings, an Excel bill-of-quantity and CNC data used to control their production machinery. They based their design on the 2D CAD drawings and a 3D virtual model provided by the general contractor and the structural engineer.

5. Discussion

Our findings make it possible to understand the range of affordances BIM technology offered its users at project level and the degree to which these were enacted in practice. While most of the project’s designers made use of BIM’s transformational affordance to create their individual disciplinary 3D models, BIM’s embedded cooperative affordance was only enacted to a very limited degree. Today’s systems such as Autodesk’s Revit® have the affordance to serve as cooperative design spaces allowing for multiple designers from different disciplines to create shared virtual BIM models in collaborative dialogue. Scholars have argued that concurrent design based on a central, shared 3D model is difficult to accomplish with current “packaged [BIM] software solutions” (Whyte, 2011). Instead of collaborating based on a central model in their BIM systems, the actors collaborated based on a variety of improvised practices. In our case study we observed, for instance, that collocated actors such as the engineers matched their model based designs by simply discussing them in their office. Others collaborated based on paper drawings created in 2D CAD. In addition, several actors exchanged and matched replicas of their individually created project models based on standard IFC file format, shared by deploying model viewers and checkers. However, presuming that BIM's embedded work sharing solutions are technically adequate for cooperative design, we can only speculate why actors opted for not making use of its cooperative functionality.

Literature reports that "*systems promoting teamwork may be rejected by people that usually work alone",* and refer to this phenomenon as "cultural misfit" of technology (Markus, 2004). It could be that BIM's embedded "work-sharing" functionality was rejected due to the fact that construction designers are not used to create designs in concurrent collaboration, but rather like to finalize designs individually before sharing them with others. A second possible explanation for not enacting BIM's inbuilt cooperative affordance could be that it simply does not fit the way in which people work in the construction industry, a phenomenon referred to as "task or business process misfit" (ibid.). If BIM's embedded cooperative functionality is unfit or counterintuitive to people's way of working then it becomes understandable why this functionality has not been enacted in practice, and why the actors deployed other solutions (model viewers or 2D paper drawings) for collaboration.

Further, none of the systems used at project level had the affordance to inform its users about the context in which the design and coordination technology was to be applied. An example for such technology could be a "communication web tool where individuals exchange and organize files as nodes in information dependency maps" (Senescu et al., 2011, p. 3) This finding does not come as a surprise since systems having these affordances are not yet commercially available. Currently, research efforts are underway exploring ways how to develop BIM into a communication facilitating software and an example for this work is the development of the "Design Process Communication Methodology" (DPCM) which has been developed based on ideas stemming from Business Process Modeling (BPM), Human Computer Interaction (HCI) and Organizational sciences (Senescu et al., 2011). In addition to the absence of systems having support affordance at project level, we found no systems having an "infrastructure" affordance useful to transfer knowledge, skills or methods to other projects or planning situations. Moreover, we could not identify systems useful to serve as a central repository providing "storage" affordances to its users. These findings are somewhat surprising as for instance shared BIM model severs or online repositories useful to exchange model drawings and information surrounding the BIM model, which have both storage and infrastructure affordances, have been commercially available to the construction industry for some time.

Apparently, the design practices of several project actors, such as the general contractor and the fire-protection engineer were based on 2D CAD technology. Other project actors interested in communicating with these two parties were required to convert their model based designs back and forth into 2D CAD drawings. Researchers argue that "the conversion of the model […] into 2D drawings" is a common phenomenon in today's construction projects as industrial practice is still in transition from 2D to 3D design (Whyte 2011). However, having two types of design objects is problematic as "…it takes extra work to get 2D plans and is not just a slice through the model" (ibid., p. 165). Moreover, our findings support that when central project actors, such as the general contractor, do not deploy 3D tools affording them to collaborate with others then the project partners begin to improvise and "bypass" these actors in their communication. In our case project, for instance, the subcontractors (massive-wood contractor and the glue-lime builder) approached either the structural engineer or the architect to establish a direct access to 3D modeling data. Thus, the general contractor's traditional role as information hub for the subcontractors was undermined by him not deploying 3D modeling technology. The fire-protection engineer's inability to participate in modeling had less severe consequences, since he was collocated with the other engineers who readily incorporated his 2D design in their 3D models.

There is high task interdependence between the designers participating in the different design stages of negotiation, generation and execution. Engineers depend on prior work provided by the architects and so forth. This fact is owed to the sequential nature of construction design in which design is gradually accumulated over time. We found that actors' possibilities to use their design systems for goal-oriented action or their "freedom of enactment" depended on when in the design process they contributed. We define freedom of enactment as the degree of flexibility which an actor has to act in a given structure such as BIM information systems (Weick, 1988). While actors working in early project stages (e.g. architect) enjoyed relative freedom in enacting their design tool affordances (in our case the architect used three different modeling systems), actors in later project stages are constrained in their ability to make goal-oriented use of their technology. These constraints stem from the necessity to work with design data previously created by others.

Examples of project actors being less fortunate than the architect regarding the freedom of enacting their tool affordances were subcontractors such as the massive wood and glue-lime entrepreneurs who were dependent on design created by their predecessors. They needed to incorporate previously created 2D CAD files or 3D models from a variety of systems into their design. Thus their capability to deploy their own systems effectively for goal-oriented action was reduced. A graphical illustration depicting that an actors' position in the design process relates to the freedom of tool affordance enactment can be found in Figure 1. We argue that choices made at an early stage of a project with regards to which tools and affordances are enacted in practice may have a profound effect on the opportunities for goal-oriented ICT mediated action at later project stages. Thus, we argue for the need to direct managerial attention at decisions made in early design stages, foreseeing their potential consequences which may constrain actors in later project stages in using their systems effectively. In addition, it seems that the case study results could be partly explained due to a lack of explicit agreement on software to be used and on the strategic management of the BIM implementation (Merschbrock, 2012). Moreover, the results may be attributed to a lack of client commitment to using BIM at project level, and the varying maturity in using advanced systems such as BIM among the individual project participants.

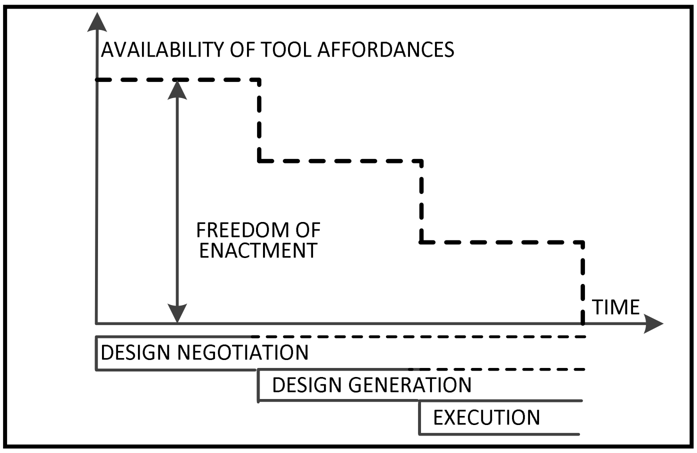

Figure 1: Freedom to enact tool affordances in construction design

We believe to have provided some practical insights helping to understand some of the weaknesses in current practice and some of the hurdles preventing practitioners from reaping the benefits of BIM technology and we have presented suggestions for how these hurdles could be overcome. Gaskin et al. (2010) provided a list of research avenues worthwhile pursuing, e.g. to study the extent to which "design routines within in a single project […] are similar and different, in what ways, and how do they mutate over time?" (p.12). We have contributed to their work by an in depth discussion of the similarities and differences of the design routines within our construction project, however, our work is limited in that we did not provide a longitudinal perspective identifying if and how these design routines mutate over time. Deploying a longitudinal perspective explaining how actors' routines vary beyond the project studied could be a worthwhile avenue for further research.

6. Conclusion

By deploying a sequential analysis it was possible to develop an understanding of the use and affordances of BIM technology in digital construction design. Despite heavy investment by most project actors in new modeling technology, several organizational and technical challenges prevail. On the technical side, the tools deployed at project level had several shortcomings in their functionality, lacking support, infrastructure and store affordances. Moreover, the cooperative affordance embedded in the BIM systems had not been enacted in practice. In addition, we found a central project actor still deploying 2D CAD instead of 3D modeling technology in design, requiring frequent transition of model based designs into 2D CAD drawings. Thus, it may be questioned if the tools used at project level were "good, complete, aligned and used and appropriately managed for benefits" (Markus, 2004). On the organizational side, we could identify many practices surrounding the modeling activity which were merely improvised "workarounds" that emerged in response to the affordances of the tools used at project level. These workarounds, in combination with the lacking tool affordances, resulted in the designers missing out on the radical improvements often attributed to BIM technology. We argue that some of the identified weaknesses can be attributed to a lack of managerial attention directed at the early stages of the project. However, our view on design routines is developed based on a single case study and interviews with a selected number of practitioners. Even though we argue that our findings have relevance beyond the case project studied, additional research studying multiple projects and contexts is needed to further validate our findings.

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