Gina Neff, Brittany Fiore-Silfvast & Carrie Sturts Dossick

A CASE STUDY OF THE FAILURE OF DIGITAL COMMUNICATION TO CROSS KNOWLEDGE BOUNDARIES IN VIRTUAL CONSTRUCTION

When can digital artefacts serve to bridge knowledge barriers across epistemic communities? There have been many studies of the roles new information and communication technologies play within organizations. In our study, we compare digital and non-digital methods of inter-organizational collaboration. Based on ethnographic fieldwork on three construction projects and interviews with 65 architects, engineers, and builders across the USA, we find that IT tools designed to increase collaboration in this setting instead solidify and make explicit organizational and cultural differences between project participants. Our study suggests that deeply embedded disciplinary thinking is not easily overcome by digital representations of knowledge and that collaboration may be hindered through the exposure of previously implicit distinctions among the team members' skills and organizational status. The tool that we study, building information modelling, reflects and amplifies disciplinary representations of the building by architects, engineers, and builders instead of supporting increased collaboration among them. We argue that people sometimes have a difficult time overcoming the lack of interpretive flexibility in digital coordinating tools, even when those tools are built to encourage interdisciplinary collaboration.

Keywords collaboration; qualitative methods; building information modelling; teams

Introduction

Introducing new digital communication and collaboration tools is a fraught process regardless of the workplace setting (Barley 1986; Orlikowski 1992,

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2000; Carlile 2002, 2004; Neff & Stark 2004; Leonardi 2009). Power relationships, cultural differences, and organizational distinctions often get reasserted at the moment of technical and social change. Problems of coordination and collaboration across knowledge boundaries remain the most vexing arena of inquiry for organizational theory.

To expand our understanding of how information and communication technologies succeed – or fail – at facilitating collaboration across organizational and knowledge boundaries, we studied a new digital tool used within large-scale building design and construction. Like many such technological changes, this assemblage of software solutions, server hardware, and social and technical processes was designed to facilitate organizational change by encouraging closer collaboration – in this case, among architects, engineers, and builders. However, it is not working as intended. This is in part because the differences in the disciplinary cultures of building design and construction are reflected within the digital, cognitive, and representational models that each discipline generates. This particular set of digital tools fails to bridge these existing, distinct disciplinary knowledge boundaries. Based on our field observations of the practices around these tools, we explain why they are failing to coordinate across these heterogeneous groups. Instead of serving to coordinate across different knowledge boundaries, this particular digital tool highlights those differences. Further, we enumerate the conditions under which digital objects can serve as 'boundary objects' – epistemic tools that enable coordination work – arguing that digital objects can bring disciplines together, but there are particular challenges when used as coordination tools as compared to non-digital, material artefacts (Star & Griesemer 1989, p. 387).

In commercial construction, building information modelling (BIM) is a digital tool and organizational process used to represent buildings in three-dimensional digital models and databases and to facilitate coordination and communication within building projects. BIM is at once a visualization tool for representing a building three-dimensionally; a database of building components that can be queried, filtered, and analysed; a collaborative communication tool for linking the various teams of experts who work in the temporary project organization of commercial construction; a tool for translating discipline-specific software files; and a collection of datasets about a building that reflect the distinct disciplinary perspectives of architects, engineers, and builders.

Within the design and construction industries, many people present BIM as a way to facilitate communication and exchange of information and to increase work efficiencies among designers, engineers, and builders. What we find in practice, however, is that while BIM is currently linking project participants more tightly together technologically, they remain organizationally divided, often lacking timely access to crucial information and decisions (Dossick & Neff 2010). BIM technology adoption can in theory and does within the right settings foster collaboration. However, even though BIM usage has doubled since 2007, work practices that support increased collaboration and knowledge sharing across organizational and disciplinary boundaries have been slow to emerge (Construction Users Roundtable 2004; McGraw-Hill Construction 2009). Instead, the technological advances of BIM are used to generate different representations and analyses of the building that remain within disciplinary silos. For example, one industry report estimates that 16 per cent of the architects are using BIM, although most are using it primarily for visualization and analysis instead for increased collaboration with engineers and builders (American Institute of Architects 2006; Gonchar 2006).

Architects and engineers have been using three-dimensional design and computer-aided design (or 'CAD') tools for decades, but only as communication within their own field using their own discipline-specific software. Architects collaborate among themselves using architectural CAD software. Similarly, engineers and builders have their own disciplinary-specific software tools for design and analysis. BIM software tools (such as Autodesk's Revit program) consolidate work from trade-specific software packages – combining, for example, the output from architectural and engineering software – to generate databases that associate rich technical information with building objects. A door in a three-dimensional CAD drawing may be beautifully rendered, but in a BIM model, the same door 'object' could contain information on the model number, the approval signatures, the delivery date, and the subcontractors questions about installation. Currently, most architects use CAD tools for design and then print out two-dimensional plans and specifications, which are still the norm for communication among people working on large commercial and institutional building projects. BIM and CAD differ primarily in the technological nature of the data-sharing and communication across the organizational boundaries and in the intended collaboration encoded into the software.

We take a 'pragmatic view' (Carlile 2002) towards studying this new technology and find that in this setting, multiple digital models are being created that are socially embedded in a complex array of contractual arrangements, professional standards, cognitive approaches, and occupational cultural divisions. The purpose of BIM – and many such collaborative software tools – is to create a digital environment in which people can think through problems together. We see BIM tools beginning to be used this way *within* the community of builders on two of the three buildings that we studied. However, the co-creation of knowledge and knowledge sharing are limited to professional communities that already share conceptual models of the building framed by disciplinary concerns of form, function, and execution. We ask in this paper why digital tools are less useful for communicating *across* these knowledge boundaries than the existing alternatives, namely paper-oriented plans and specifications. We find in this case that digital models do not allow for the necessary interpretive flexibility that enables adjudication among the carefully balanced different perspectives of the building. For the broader study of technology and organizational communication, our case suggests that boundary-spanning collaborative tools should be designed with an eye towards maintaining the multiplex interpretations that exist across organizations. Within commercial design and construction, our research has implications for understanding why collaborations fail and for designing both new digital tools and the socio-technical arrangements that allow for the multiple, simultaneous, and competing perspectives of the participants using them.

This paper proceeds as follows. First, we briefly outline the literature on communicating across knowledge boundaries and review some of the key sociologically informed findings on the particular technology that we are studying. Then we discuss our three field sites and the methods we used to approach them. Next, we outline the process of virtual construction and the implications of this technological and social process for collaboration. Finally, we conclude with the lessons from our cases that can be applied to inter-organizational collaboration and technological change more broadly.

Communicating across boundaries

As buildings have become increasingly complex, a panoply of specialists have emerged with highly differentiated skills and tasks on large building projects. Building information in the form of plans, documents, and drawings is communicated across many professional and organizational boundaries, and the industry needs tools that can help bridge knowledge gaps and facilitate collaborative work practices. Traditionally, the lead architect publishes and distributes two-dimensional plans to the consultants periodically throughout the design, and formal construction document sets are compiled, published, and distributed throughout the construction. Information is lost as it is shared between organizations. At each transfer point, the recipient of the two-dimensional drawings has to study and interpret architectural representations, which are governed by very complex and deeply embedded standards of practice. Even when the drawing is generated using CAD software, any digital data used to support or document the drawing are left on the computer in the architect's office when these drawing sets are printed out and shared. Consequently, throughout the network of specialists, there are inefficiencies where engineers or builders digitally 'rebuild', using information from drawing sets that they could otherwise receive electronically from the original digital data. BIM provides an opportunity to both simplify the representational standards of practice and expedite the work flow with direct digital exchange of information by linking participants in a project to share digital information directly.

While it may seem simple to translate an architect's three-dimensional computer designs into a shared collaborative information and communication tool, research has found that the choice of particular media or a change in medium can reinforce or redistribute task area boundaries among different occupational groups and cultures (Bechky 2003a,b). Particular standpoints can become associated with the format of the representation of knowledge or encoded into a new communication technology tool (Henderson 1991; DeSanctis & Poole 1994; Kellogg *et al.* 2006). Within building design and construction, paper is more than a medium for communication – it is integral to how people in the field think and negotiate across the many disciplinary knowledge boundaries that exist in the field (Harty 2008). Two-dimensional paper plans and specifications are a particular kind of object in work practice, which are stable enough to mediate among people within a project and outside of it, becoming an active part of the continuous sets of negotiations and alignments around attempts to innovate and reinforcing the shared frames of reference among designers and builders (Harty 2005, 2008; Beamish & Biggart 2006).

The shared frames of reference in building, however, support vastly different conceptions of what a building should and could become. As members of professional communities, architects, builders, and engineers privilege different aspects of a building, such as form, execution, and functionality. In this way, a building project is 'heterogeneous, contingent, unstable, partial, and situated', comprised of elements that are 'not reducible to the same logic' (Marcus & Saka 2006, p. 104). It is in such an environment of multiple logics that enough mutual understanding must occur to facilitate collaboration and communication. Designs for buildings have an 'unfolding ontology' of technical, social, and aesthetic forms of knowledge that need to be developed and aligned (Ewenstein & Whyte 2009).

Within the academic literature on construction engineering, there is some debate over whether BIM technology can bridge these boundaries. Harvey argues that digital models 'can credibly aspire to become a valuable mediator in the planning and construction process, stable enough to create some common ground for discussion, flexible enough to reflect and respond to diverse opinion, and credible enough to work for diverse professional and public viewers' (2009, p. 260). Taylor, too, takes a practice-theoretical approach in arguing that the co-creating a building information model can foster an organizational process that improves collaboration among architects, engineers, and builders (2007). However, within current practice in the field, there is little evidence that this co-creation is taking place across the disciplinary knowledge boundaries that separate architecture, engineering, and construction (Dossick *et al.* 2009; Dossick & Neff 2010). We have argued elsewhere that the ways BIM is used in current practice link project participants more tightly technologically, even as they remain organizationally divided, often lacking timely access to crucial information and decisions (Dossick & Neff 2008, 2010). While Taylor describes the work practices of BIM as the co-creation of a single virtual model, in current practice we find that BIM is a series of epistemic objects, authored without the co-creation of knowledge across boundaries and without significant input from expertise outside a distinct disciplinary realm. While this process of modelling could potentially serve the informational needs of a diverse set of actors from different companies and knowledge communities at different points in time during the project, from our research we see something quite different in practice (Dossick & Neff 2010).

Boundary objects are useful theoretical constructs to think about how conceptual knowledge work happens at the intersections of distinct communities of practice. Boundary objects are flexible epistemic artefacts that 'inhabit several intersecting social worlds and satisfy the information requirements of each of them', adaptable to different viewpoints while being robust enough to maintain identity across them (Star & Griesemer 1989, p. 393). Boundary objects act as 'anchors or bridges, however temporary' across different groups with different goals, objectives, and purposes (Star & Griesemer 1989, p. 414). Several scholars have argued that boundary objects are most effective for collaboration and coordination when they are actual objects – tangible and concrete, but still able to maintain multiple, epistemic definitions so as to be accepted and usable by the groups they are trying to bridge (Carlile 2002; Bechky 2003a,b). They help people work across knowledge boundaries through assisting with the processes of 'transferring, translating, and transforming' (Carlile 2004) or alternately the 'display, representation, and assembly' of knowledge (Kellogg *et al.* 2006). As Kellogg *et al.* describe, this entails making visible the work to others, rendering heterogeneous ideas into a form legible for other people's interpretations and use, and juxtaposing 'their diverse efforts into a provisional and emerging collage of loosely coupled contributions' (2006, p. 38).

The boundary object as a concept describes an epistemic tool that is robust enough to uphold any necessary distinctions for knowledge specialization while still providing cohesion for the communities around that expertise *and* remaining flexible enough to link these distinct communities of practice to allow for limited, or 'relatively bounded', collaboration (Harty 2005, 2008). Yet, there has arguably been a tendency by scholars to overplay the interpretative flexibility of boundary objects instead of the constraints and structures that they may impose. That is, the artefact serving as a boundary object most likely presents technical, temporal, organizational, or cultural affordances and constraints in such assemblages. The question remains when can digital artefacts become epistemic tools to overcome these knowledge and organizational boundaries and when might they make these boundaries even more explicit.

Setting and method

We studied three building projects using a variety of qualitative research methods at a moment of transition between paper and digital representations of buildings. Hill, Valley, and Lab are pseudonyms for three urban large-scale construction projects in the same city that we observed from March 2007 to November 2009. Hill is a 450,000 square foot mid-rise complex commercial office building; Valley is a

300-unit, mixed-use residential high-rise building; and Lab is a 90,000 square foot complex laboratory building. For each project, we observed a series of coordination meetings involving eight to 10 people led either by the general contractor or by the architect. For Hill and Valley, we observed the detailed design meetings of the mechanical, electrical, and plumbing (MEP) subcontractors. These detailers used BIM to coordinate their designs. For Lab, we observed the schematic design and pre-construction meetings of the owner, architect, contractor, as well as occasional stakeholder meetings. These meetings did not use BIM. A research team of one faculty researcher and one graduate student was primarily responsible for attending each meeting. The research team noted technology use within the meeting, interactions among meeting participants, and discussions about project logistics with particular focus on how collaborative decisions were made among the project team and how knowledge was communicated across disciplinary boundaries. Detailed field notes were written about each meeting, and these were analysed using an emergent, iterative coding schema based roughly on Glaser and Strauss' notion of 'grounded theory' (Glaser & Strauss 1967). In addition, both spontaneous, informal interviews and 15–40 minute formal interviews were conducted with project participants to understand further the cultural and organizational clashes occurring within the teams. We also collected information that circulated among meeting participants, such as logs of clashes, emails about coordination schedule, meeting minutes, and digital snapshots of the building model. We did office observations of the architects and engineers on the Lab project and observed the general contractor teams on the Hill and Valley projects (Table 1). **Q6**

TABLE 1 Comparison of representations

	The building	*Physical model*	*Paper drawings & Blueprints*	*Digital model*
Material Stability	In process	Yes	Yes; once printed	No
Temporal fixity	In process	Yes	Once printed; but multiple versions over time	No
Interpretive flexibility	Yes; different meanings to different disciplines	Less; but able to be manipulated	Open to interpretation	"Overdetermined"
Malleability	Becoming fixed; input from disciplines	No	Iterative; versions	Yes

We also interviewed 65 architects, engineers, and builders from five major metropolitan areas in the USA who were not involved in these projects and who had expertise or experience with BIM or who were recognized experts in their field. We used snowball sampling to find respondents in commercial construction with experience using BIM and asked open-ended questions about organizational culture, use of technology, and communication styles to ascertain both how BIM was being used and how our respondents framed the collaboration process. These 60–90 minute interviews were recorded and fully transcribed, with the transcriptions coded and analysed for recurring themes using ATLAS.ti.

In the interview data presented below, all interviews refer to these 65 people *not* directly involved in our three cases, unless otherwise specified, and all field observations refer to these three cases, unless specifically noted otherwise.

Virtual building and the reduction of interpretative flexibility

In all three cases that we observed, paper documentation was still important, although in the Hill and Valley projects, the digital display of the BIM model of the mechanical systems anchored most MEP coordination meetings that we observed. The comparison between those meetings and the Lab meetings, which were oriented around paper plans and sketches, allows us to see the challenges of using BIM models to communicate across knowledge boundaries. On the one hand, BIM models made some aspects of communication easier by clearly delineating responsibility and making explicit particular design requirements, especially when these involve computational analysis or complex displays. While these more explicit digital models enabled a greater capacity to resolve conflicts or test possibilities among participants, they also inadvertently encouraged working in disciplinary silos to manipulate individual scope without collaboration across boundaries.

One reason for this is that digital models may have less *interpretive flexibility* than paper plans. As one architect explained, in BIM, ‘It is what it is. You cut a section, if that thing’s close up and if it’s there, it’s going to show up’ (architect interview). Interpretive flexibility – or the ability for multiple people to draw their own interpretation from the plans – is important within the design process. He continued,

> You can do this in 2D really well, just draw what you want. It doesn’t matter if it’s really correct or it’s coordinated to anything, because at this point you don’t want that to be that way. You’re trying to communicate design intent not accuracy. *Because you’re just formulating idea, so you’re trying to keep things vague*. It’s an important part of the design and workflow. But when you’re doing the BIM model there’s no room for that anymore
>
> (architect interview).

This tension between the precision of what is presented digitally and the need to keep some negotiations open and vague strikes to the core of the collaborative challenge that BIM faces in implementation. The same technological affordances of BIM that encourage specificity may also hinder collaborative work by privileging certain visions or representations of the building over others.

At the meetings oriented around paper-based drawings, there was inevitably some hermeneutic explication of what the documents at hand meant or could mean. A refrain that reflected the power of three-dimensional modeling, which we heard in meetings and was told by respondents, was ‘What elevation are you at’? – a question that literally attempts to anchor different spatial conceptions within the building onto the same point. With paper, meeting participants had some openness to infer what drawings could represent or how they might function in three-dimensional space. With digital models, this interpretative flexibility was taken away and was replaced with explicitness about what was possible for the building.

> The old [meetings] . . .everybody is in a bad attitude and they’re, you know, ‘What elevation are you at? I see that your line is hitting mine. What elevation are you at?’ So, lots of calculations. ‘OK, well, my top of height is at this elevation and I transition. . .’. And the other person is saying, ‘Well, I’m at this.’ So they’re both mentally putting together exactly where did that occur and how many inches does one of them need to move in order to solve that
>
> (builder interview).

The introduction of new technologies changes the dynamics of the coordination across organizational boundaries, which is a large part of the collaborative work of architecture, engineering, and construction. One builder told us,

> And what you’re doing here with the 3D is enabling the communication – ‘Here’s what I see, here’s how I see that interacting.’ Now it’s in 3D and it’s so much easier for everybody else to communicate and understand, ‘Oh, that’s what you mean.’
>
> (Builder interview)

According to another, BIM is ‘just different, it changes the landscape’, because,

> Well, in 3D, it’s plain as day. You can see it and it’s very easy for people to approximate. . .. So it’s a completely different conversation, no more is it an adversarial – ‘what elevation are you at?’ – It’s more a matter of ‘Oh, well, we’re just barely hitting there, I could just move it a ways,’ or ‘No, that’s a real issue.’ Now you pull somebody else into a discussion, it is an issue of there just isn’t enough ceiling space. But even that kind of

> thing, you know, it's not an adversarial conversation between those two people, they're not fighting for that space, they are now saying, 'Hey, Mr. Architect or Mr. Designer, you didn't give us enough room for both of these systems.'
>
> (Builder interview).

Thus, BIM facilitates communication across knowledge boundaries by making explicit the problems and conflicts between different building systems – builders can visualize the work among themselves in three dimensions and can show these problems to architectural or engineering designers.

In making interpretations of the building explicit, the digital model 'performs' the building as both a complex socio-technical object, as an embedded process, and as a material object that does not require interpretation from others. In an engineer's assessment,

> We're no longer drawing, we're no longer representing *a* building, it's no longer representational.... What we draw is the thing, just scaled down ... that's what it is, that's the thing. So any time you have something that's representational, right off the bat it means that somebody has to interpret it.... *You no longer have to interpret what I'm doing*
>
> (engineer interview).

However, what an engineer does is at conceptual odds to what others do on a project. That is, their need for BIM to serve a particular conceptual function might preclude others from fruitfully sharing their model of the building, as we will see below. The representational clarity of BIM, though, belies the continuing openness, negotiations, and fluidity around both the model and the building through the design and construction phases. The computational power of visualization and representation of this knowledge, as we will see in the next section, has outpaced the industry's ability of, borrowing from Carlile (2004), 'transferring, translating, and transforming' these distinct forms of building knowledge across professional boundaries. That is, the digital model is more powerful than the organizational assemblage to act upon or transform it meaningfully across knowledge boundaries. The gap between what BIM can show and what people using BIM can do about what they see is one of the main reasons why the technology currently fails to bridge across organizational and knowledge boundaries.

Divisions, silos, and competing visions of the building

In both the Hill and Valley projects, MEP detailers from different subcontracting companies used BIM for the detailed design of the mechanical systems of the building, sharing their 'detailing' on a single digital model of the building 'built' by the general contractor. In this regard, the MEP detailers co-created a single digital model. However, they became aware of their division from the rest of the project – and of organizational gulf between their BIM model and the rest of the project information flow – when they sought information from architects and engineers to help them complete their model and the design tasks within it. While work within the MEP team was technologically tightly coupled, it was loosely coupled from the rest of the project organization. Using the BIM model, detailers from different companies could see each other's work, but they were frequently frustrated by their organizational separation from project architects and engineers. For example, using the BIM model, the mechanical subcontractors on the Hill project proposed several small design solutions that they estimated would have made project construction more efficient. However, their digital models were not shared with architects and engineers, and the detailers' suggestions were not incorporated into the final design.

For both the Hill and Valley sites, the MEP teams became frustrated when engineers and architects did not answer their questions, reply to their requests for information, or make decisions quickly enough to allow them to get their own work done on schedule. The MEP detailers' contribution to joint knowledge production was rendered moot by their starting design work after engineering and architectural design was practically complete. Having used BIM to closely coordinate spaces among themselves only compounded their frustration since they could see what they thought of as errors in the model as well as problems with the design of the building and mechanical systems, but they could not get approval from the architect (Hill) or engineer (Valley) across organizational boundaries on their approach to solving the problems. The model exposed the MEP team's technical problems while making visually explicit the organizational challenges that they faced. BIM, as a new technology, cannot yet overcome sociotechnical arrangements that prevent knowledge sharing across organizational divisions.

For the Lab project, we observed the collaboration between the architect and a panoply of engineering and technical consultants at a much earlier stage in the design process than for Hill and Valley. While BIM could be used in this stage, the Lab project did not employ it, instead relying on more traditional forms of representation and communication across disciplinary boundaries. While the architect and several of the engineers created digital models of the Lab building, these were used only for analysis within their own organizations and professional knowledge communities – not for communication across the inter-organizational, interdisciplinary design and construction team. In the Lab project, as with both Hill and Valley, BIM existed only in disciplinary silos. Architects, engineers, and builders utilized digital models for their own distinct purposes rather than sharing and collaborating within the BIM digital environment as it had been designed to do. As such, the practices that emerged around the technology were not those for coordinating across knowledge boundaries or (with the exception of the subcontractors who worked for the general contractor) across organizational boundaries. During our interviews, several respondents talked of the need to closely guard their digital models from collaborators in other disciplines, arguing that their own version of the model would be too specialized, could be misinterpreted, or might misrepresent the accuracy of the information or designer's intent within the model. Those who opposed the sharing of models maintained that their disciplinary particular use of BIM made sharing models difficult if not impossible. Engineers said that they would want to maintain BIM for the purpose of analysis. Builders used BIM for the estimation of building costs and materials, and as well as for efficient execution of the building plans. Architects used it for the conceptual work of designing the building. Despite being a collaborative tool, this digital technology was used to help confirm professional distinctions.

A Lab project architect highlighted the benefits of using digital modelling in this way, 'You can really only understand the building when you go through the model like this – there's a real benefit to building it yourself' (Lab architect, field notes). Additionally, even within the same firm, the reason behind a particular BIM model can make sharing difficult. The BIM director of a general contracting firm explained that the same three-dimensional digital models used for estimation within his firm might not be useful for people elsewhere in the organization. He argued that the cost estimation use of the model would not translate to a use for on-site construction, even within the same company and within a community of builders:

> We are finding more and more reasons that our estimating models are just [ ] not the same as your coordination model.…We are not going to share the estimating model with the field guys because we've run into a number of situations where they get a hold of an estimating model and the beam doesn't slope or the floor doesn't slope and then they are pointing back to us and saying, 'Hey, wait a minute, we are coordinating to this.' So, we really need the field people to say to somebody involved in the scope, 'What is the model for? Is it for a quantity [estimate of materials?] Then you don't need that slope. Is it for coordination? Then absolutely you need that slope.' Somebody to go through that thought process, and say 'Is this model good for that purpose?'.… And that's where we are going to say, 'No, you can't have this model because it is not good for your purpose.'
>
> (Builder interview).

Purpose-driven modelling makes collaboration more difficult, even as the knowledge and data of these specific BIM models appear useful to others. Within the Hill project, the MEP detailers requested from the structural engineer a copy of the BIM models showing the steel structure in order to coordinate with their designs and received, instead, a two-dimensional print out stamped 'Not for

Construction Purposes', precisely because of the same problem of translation of knowledge across disciplinary boundaries. BIM makes these designs more explicit, but the shared conventions and language for that knowledge translation work does not yet exist as it does for paper-based plans and specifications. An architect responsible for his firm's BIM modelling explained this gap between engineering and architectural visual languages in models:

> An engineer has a very focused way of looking at the building, specific systems that they are interested in, and they are charged with designing. It's important for them to be working in the same medium as everyone else, which is the whole point of BIM – making sure that everyone is working in a shared medium, shared space. That requires them to rethink the way that they work because their specific way of looking at something might be great on its own but needs to be kind of tweaked a little bit to fit into a comprehensive view of the project. So for example, an engineer also wants to model in an analytical way. They'll draw a line which represents a duct work, a line that connects to something else and so when you're looking at that line in this duct work drawing, that line has meaning. But when you put that line into the space sitting next to a piece of structure, it has absolutely zero meaning, so it's important that they think of things in a kind of physical way as well as an analytical way.

Meaning making across disciplines is still a challenge that modelling in BIM faces, in part because BIM makes particular aspects of design explicit.

Knowledge within BIM can also encode decisions that are not transparent to others or shut off negotiations around those decisions. In this particular setting, architects voiced the concern that a three-dimensional digital model reflects choices that were made to complete the artefact, not necessarily to represent the shared knowledge or decisions of the group. For example, when walls are presented in blueprints, they do not need to have a colour 'painted' on them as they do in a three-dimensional model. Digital models may suffer from *overdetermination*, meaning seemingly technical choices that have political or organizational ramifications take on unintended significance and permanence. As one architect explained,

> There's almost too much information in them so you start to see more . . . ambience and there's a certain distrust, I think, when you see those things. But you can drop in all kinds of things now, beautiful plant materials and – so there's what I'm talking about is that there's a kind of abstract nature to a physical model and it's very clear it's an *abstract* version of the design. Whereas a fully rendered physical model, it comes so close to reality that there's a perception that this is *exactly* what they're getting. I think certain people when they look at that, they're way beyond that this is actually an

> abstract idea that has to still be developed quite a bit. There's kind of a gap there, that the architect is really not to where the rendering is showing it to be.…
>
> *Interviewer:* Have you been in that situation where you're showing your client a 3D rendering and they misunderstand it and think you've already made all the –
>
> *Architect*: Yes. 'Oh, I thought we were going to have green walls with wood doors', and We'd say, 'No, that was just something we put in the model because we had to. We had to show something'. Whereas, in the physical model it would be [made of] balsawood; it wouldn't even be any color and it wouldn't be any glazing shown in it.… What I try to do is to explain to a client what this really is, that it's not as developed as it looks. But you have to make sure that you do that.
>
> (Architect interview).

Increased information presented to others on the project is not necessarily rich with rationales or logics, making joint problem solving difficult. Thus BIM fails here to do the work of bridging these knowledge gaps so that one model might represent the shared knowledge of the group.

However, as with the details, the digital model also makes explicit the vision that each discipline has about the building. Several respondents familiar with BIM used the verb *build* to refer to making digital model – one contractor going so far as to refer to the digital process as 'building it before we build it' (Valley general contractor interview). Each set of representations reflects a disciplinary vision of the building – a cognitive map of what the building is becoming – but cannot necessarily perform the translation or transformation of knowledge across disciplines towards this goal. Architects want to be able to create a finished design from their concept, working through schematic drawings and representations. Engineers need detailed analysis on the function of the building. Builders plan how the building will be executed using such representations. To each, these cognitive distinctions of what a building is and what it will become have been fruitfully represented both in blueprints and in digital models. However, unlike the more interpretively flexible paper plans, BIM's explicitness cannot simultaneously represent these cognitive distinctions. One architect we interviewed addressed this when he conflated the ability to analyse within the software with the software 'knowing' what a building is, saying that there is a 'huge difference between drawing symbolic information that represents something in a person's mind versus modeling structured information that computer programs can go in and do more with and analyze because they are object oriented and because the software actually makes it such that software tools know what a building is' (architect interview). The building is different things within different discipline-specific software packages, and it is these multiple representations of the building that BIM attempts to combine, however imperfectly.

Boundary objects are useful when they can produce interpretive flexibility across heterogeneous knowledge boundaries, but BIM and the practices around BIM are not currently producing the socio-technical conditions for this flexibility. As a visualization tool, BIM models have *less* interpretive flexibility across boundaries, drawing organizational divisions and knowledge distinctions even more clearly. As the building appears more transparent and less 'problematic' in BIM, it is less open to interpretation than in paper plans.

Conclusion: digital tools, overdetermination, and impediments to collaboration

There are several ways that digital tools complicate collaboration. First, the visualization of work that takes place in environments like BIM may make explicit organizational divisions. While 'mutual shaping' (Boczkowski 1999) of users and technology may occur over the process of technology implementation, the outcomes of such endeavours are far from settled or known at the outset. While the BIM digital environment was intended to improve collaboration, it is currently being used primarily *within* professional communities, not across them. While the MEP subcontractors successfully used a single BIM model across different companies, they were frustrated at the divisions that BIM was not able to overcome through closer coupling of disciplines technologically.

The failure of BIM to bridge knowledge gaps across organizational and disciplinary boundaries challenges the intended use or industry vision of BIM as an inter-organizational collaborative tool. These failures are organizational, technological, and social and become inextricably woven into the building process. The work of collaboration and communicating across organizational boundaries is not fully understood in this new environment and needs to be further researched and understood.

Our case suggests that digital objects may lack the material stability and the interpretive flexibility to maintain negotiations across knowledge boundaries. While there are many instances where information technology may improve collaboration and communication within teams, it is not due to its ability to span knowledge boundaries. For digital technologies to do so, they need to have the ability to remain relatively stable as they transit across these knowledge boundaries while being relatively open to interpretation across multiple groups. The overdetermination and flexibility of the digital models that we studied hindered the groups' ability to work together serving at counter-purposes to the intentions behind BIM's design.

For scholars, our research suggests that technology-enabled collaborations should be examined for their ability to integrate multiple perspectives, knowledges, and standpoints. For practitioners, our findings point the way for more flexible, open technologically enhanced work environments and suggest that new tools for collaboration be designed with their interpretive flexibility in mind.

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Gina Neff is an assistant professor in the Department of Communication at the University of Washington. *Address*: Department of Communication, University of Washington, Box 353740, Seattle, WA 98195-3740, USA. [email: gneff@u.washington.edu]

Brittany Fiore-Silfvast is a PhD student in the Department of Communication at the University of Washington. *Address*: Department of Communication, University of Washington, Box 353740, Seattle, WA 98195, USA. [email: brittany817@gmail.com]

Carrie Sturts Dossick is an assistant professor in the Department of Construction Management at the University of Washington. *Address*: Department of Construction Management, University of Washington, Box 351610, Seattle, WA 98195, USA. [email: cdossick@u.washington.edu]