

**Process Innovation Through Practice:
The Messy Work of Making Technology Useful for Architecture, Engineering and
Construction Teams**

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Abstract

Purpose: Through the study of visualizations, virtual worlds, and information exchange, this research reveals the complex connections between technology and the work of design and construction. The authors apply the socio-technical view of technology and the ramifications this view has on successful use of technology in design and construction.

Approach: This is a discussion paper reviewing over a decade of research that connects three streams of research on architecture, engineering, and construction (AEC) teams as these teams grappled with adapting work practices to new technologies and the opportunities these technologies promised.

Findings: From studies of design and construction practices with Building Information Modeling and energy modeling, the authors show that given the constructed nature of models and the loose-coupling of project teams, these team organizational practices need to mirror the modeling requirements. Second, looking at distributed teams, whose interaction is mediated by technology, the authors argue that virtual world visualizations enhance discovery, while distributed AEC teams also need more traditional forms of 2D abstraction, sketching, and gestures to support integrated design dialogue. Finally, in information exchange research the authors found that models and data have their own logic and structure and as such require creativity and ingenuity to exchange data across systems. Taken together, these streams of research suggest that process innovation is brought about by people developing new practices.

Originality: In this paper the authors argue that technology alone does not change practice. People who modify practices with and through technology create process innovation.

Introduction

Over the past decade, as new information technologies have been introduced to the AEC industry, they have been in tension with established norms of practice, including those set up by contractual standards and case law (e.g., the separation of design intent from construction means and methods) as well as social and organizational norms that frame team member expectations about how they should engage with others on a project. In this discussion paper the authors review three interconnected streams of empirical research conducted over the last decade. These streams focus on three areas of sociotechnical data practices where careful consideration of—and significant investment in—team and firm organization and communication can lead to process innovation: how to organize to make data and analysis meaningful, how to visualize to make data and analysis meaningful, and the required human labor needed to make information technology work.

First, in studying the emergent use of technologies such as Building Information Modeling (BIM) and energy modeling, the authors found that these new analysis tools required experts to organize in a more collaborative manner both to produce meaningful output from the models and to understand the ramifications of the results of the modeling and analysis. This process of collaboration guided decision-making in design and construction teams. Second, when the authors studied distributed AEC teams, the authors found that new visualization tools enabled additional ways to communicate design ideas and analysis. These new visualization tools do not replace traditional, two-dimensional forms of representation and the discussions and interactions around sketches. New three-dimensional representations did multiply the media available to teams for reviewing design and construction alternatives. However, sketching and gestures were still essential practices to support productive AEC team interactions around new kinds of visual media, and team members discovered and explained problems and vetted new design proposals through these practices. In the third stream of research, the authors explored the processes of repair and breakdown in the context of information exchange (Jackson, 2014; Tanweer et al., 2016). From this work, the authors argued that there is a significant amount of work required to get new kinds of data to “work,” as was realized in studies of exchanging BIM data across design, construction, and facilities maintenance systems.

This paper draws from three streams of research and reflect on how experts use models and data in design and construction of the built environment. These interconnected streams of research confirm emerging scholarship from the broader field of critical data studies: Data are not absolute; they are constructed in team and firm processes. Whether it is a BIM manager looking to consolidate subcontractor's models, an energy modeler seeking to improve building performance, or an operations engineer looking to use design documents, they must use reflection, creativity, patience, and expertise to make data-driven tools work and create new ways of working that leverage new technologies for more effective and innovative collaboration and communication. The next two sections review the building industry challenges and theoretical gaps in which these three research streams are situated.

Models and Information Exchange in the Construction Industry

Engineers, architects, and construction professionals are trained in different approaches, processes, and methods for problem solving. The interaction among the disciplines of engineering, architecture and construction is fragmented (Henisz et al., 2012). Over the past two decades, the construction sector has been criticized for a lack of process innovation (CURT, 2004) and stagnant productivity (Teicholz, 2013a). Improving information exchange and collaboration has become a national mandate within the industry (Federal Highway Administration, 2012; GSA, 2007) and is thought to be a way to answer this process innovation gap. However, in the building sector, the adoption of new tools, such as BIM, have yet to spark the desired process innovation and productivity improvements in the design and building process, even though industry trends point to increased integrated practices among designers and builders (*SmartMarket Report*, 2012; SmartMarket Report, 2014).

BIM is 1) a product or intelligent digital representation of data about a facility; 2) a collaborative process; and 3) a system of information exchanges, workflows, and procedures (buildingSMART Alliance, 2015). BIM tools, technologies, and standards have developed, but researchers and practitioners have yet to define the best practices for achieving collaborative understanding that results in innovation in design and construction processes.

Many propose that process innovation—improving how the industry designs and builds—will come with more integrated communication between designers and builders (CURT, 2004; GSA, 2007; Teicholz, 2013b). Architects and engineers understand systems and performance criteria, while construction knowledge is the builders' expertise. Process innovation in construction requires closer integration between design and construction planning and better communication of discipline-specific knowledge. For example, in recent years the US has experienced a resurgence of prefabrication (*SmartMarket Report*, 2012), which requires close coordination and planning between design and fabrication (Azari et al., 2013). Leveraging tools such as BIM, builders can conduct “constructability” reviews that include clash detection, construction sequencing, and transportation and construction site logistics planning that help designer and builders solve problems and innovate for efficient and effective construction processes that minimize time and costs. However, innovations of processes often require industry-wide change as Merschbrock and Wahid, (2013) found that design decisions made earlier in the process limited builders' practice innovations as they use that data and information for fabrication. Solving *how to best use* new visualizations and information exchange technology could lead to better process innovation across the industry.

Computational advancements have enabled more sophisticated modeling, such as comprehensive computational fluid dynamics modeling for complex facilities (Messner et al., 2006). Recent challenges for using such tools within industry have developed around the information technology processes such as data exchanges to allow interdisciplinary teams to work concurrently (Kiviniemi et al., 2005). Some scholars, including us, have studied social interaction with and around these tools and observed emergent practices as to how and where people work (Dossick & Neff, 2011; Khanzode et al., 2008; Neff et al.

2010). For example, Leicht *et al.* (2007) found that industry members, collaborating using BIM to solve an energy efficiency problem, identified BIM to be most valuable during the stages of problem solving when it was most heavily used during communication by a given team. Furthermore, even when BIMs make some things more explicit, models revealed gaps in collaborative understanding across disciplinary boundaries or rendered familiar assumptions “invisible” (Dossick & Neff 2011; Whyte, 2008).

Collaborative Design Leads to Better Solutions

Design is broader than problem solving. Design involves recognizing a problem, formulating it, determining the method to solve it, and implementing the solution (Mitroff, 1998). The use of interdisciplinary approaches for design has been encouraged for some time from a variety of sources including ABET (ABET, 2016) and the National Science Foundation (NSF, 1995). The increasing complexity of designed object, such as buildings, requires multidisciplinary teams of engineers, designers, and specialists from several firms to collaborate with new modeling and analysis technologies (Schaffer *et al.*, 2008). Furthermore, decision-making in interdisciplinary teams is an integrative process with multiple interdependent systems. Interdisciplinary design is one of the most complex cognitive activities in which humans engage with each other, use sophisticated reasoning about specifications, and determine how the systems satisfy the project parameters (MacLellan *et al.*, 2013). Lack of complete knowledge of subsystem interactions add to the complexity of design (Pandey and Mourelatos, 2011). Participants possess an implicit set of technical values and representations that filter communication during design team interactions. As a result, interdisciplinary design is an intersection, not simply a summation, of participants’ contributions, and as such this process can be both an immense challenge and a source for novel ideas.

In the past decade of research, the authors approached the study of information technologies in construction with insights from Science and Technology Studies (STS). For example, scholarship from STS suggests that information technologies can stabilize meanings (Dickey *et al.*, 2006). However, for complex interdependent tasks, technologies must support frequent interactions and meetings (Daft and Lengel, 1986); participant awareness of, access to, and the ability to relate to the design work of others (Fischer, 2006); and real-time activities that enhance others’ work, including informal, spontaneous, or coincidental exchanges of information (Kraut *et al.*, 2002). The authors have termed these interactions “messy talk,” and identified the challenges information communication technologies have in supporting them (Dossick & Neff, 2011; Dossick *et al.*, 2015). Other design collaboration scholars argue that real-time interaction is crucial for timely and rapid iterative design, brainstorming and problem-solving tasks (Fruchter, 2005). While BIM thus serves as a rich artifact through which teams could potentially develop a collaborative understanding, the means to understand and promote the tacit elements required for novel design ideas are not clear to scholars or practitioners. It is this gap that the authors seek to address in this paper in three parts. First, Part I discusses findings from AEC teams creating and collaborating with BIM and energy modeling studies. Second, Part II presents research around globally distributed teams and extends the findings that mutable and abstract representations are important for shared brainstorming and design development

activities. Finally, in Part III the authors discuss information exchange and the work required to make the data work through data extraction, data integration, and data mapping.

Part I: Collaboration with Technology in AEC Teams

In this section, the authors summarize key findings from the past decade of research. This research stream consisted of two large research projects using parallel methodologies. One project focused on BIM and the other on energy modeling. In this research the authors conducted ethnography (BIM: 5 AEC teams across 3 projects; energy modeling: 3 energy modelers across 18 projects). The authors triangulated their ethnographic observations with interviews of AEC industry experts (BIM: 125 interviews; energy modeling: 20 interviews). For the BIM and collaboration project, the authors conducted a QCA study on 33 US AIA COTE Award winning cases to explore the relationship between BIM usage, interdisciplinary collaboration and high performance building outcomes. In the study of energy modelers, the authors compiled 7 cases of high performing hospital projects to uncover the relationship between energy modeling work and key social and organizational variables that helped teams and owners achieve aspirational energy goals.

Through these research projects the authors observed the organizational work that team members needed to do to bring multiple subdisciplinary components together. Throughout both the teams working with BIM and those working with energy modeling, the authors saw a need for team organization to mirror the technical coordination and analysis. Opposite to the belief and hype of some, the technology did not replace the need for close interaction between disciplines; quite the opposite, information technologies required teams to work more closely together. In sum, expertise is only *represented* in the technology. For meaningful design and construction work, experts need to work together with the models and visualizations that are the material product of their work.

This section begins with setting the organizational and technical context the authors observed on project teams using BIM and Energy Models. In these studies, the authors observed organizational challenges that arose from conflicting obligations between project, company, and task scope (Dossick & Neff, 2011). The authors also observed a sociotechnical context in which modeling data was inherently constructed; that is, the production of model data and translation of model results are only made meaningful and actionable through the communication practices of teams. This context created another challenge: how to increase and expedite the flow of information needed to build models and make their results meaningful to others. These two concepts, conflicting obligations and the constructed nature of data, set up the challenges and realities that teams face as they work together to design and construct facilities.

In the following paragraphs, the authors summarize key contributions from the studies of BIM and energy modeling teams. Teams implicitly and explicitly strategically managed these challenges through, *leadership*, *boundary spanners*, *messy talk*, and *interpretive flexibility*. First, the authors found that the projects rely on leadership to overcome conflicting obligations. The owner has a particularly important leadership role as a technical boundary spanner—placing the owner in key position of setting the aspirations

for the project as well as an important member of the team who has technical contributions to make. Next, the authors described messy talk: the types of knowledge work design and construction teams need to do. Finally, the authors introduced a nuanced relationship between more detailed visualizations and the need for abstract representations for interpretive flexibility. Together, these strategies that manage organizational and technical challenges required tight coupling between teams, owners, and technologies for enhanced information exchange and increased shared understanding around project problems and solutions.

The Context of Project Teams

In the authors' research on BIM and collaboration, they saw teams working through conflicting obligations between project goals, their own work tasks, and their own company's interests (Dossick & Neff, 2010). In short, in the BIM coordination teams the authors observed, the Mechanical, Electrical and Plumbing (MEP) subtrades were isolated from the project leadership and decision-making, where the designers and owners did not meet with them for coordination. At the same time, the modeling work they undertook made explicit the close interrelationship between building systems where the MEP systems wove through architectural and structural components of the building. In their isolation, they were not able to influence the architectural and structural systems and as a consequence the authors saw MEP experts pull away from what was best for the project and focus on optimizing their own scopes of work, always leery of putting their company at risk while they felt pushed by project decisions that were out of their control.

In energy modeling work, the authors observed energy modeling engineers analyze designs and then translate the results to architects and owner representatives. These AECO teams then synthesized the analysis into the broader design development process. As energy engineers and their modelers negotiated with teams over model assumptions and strategies for translation, the authors found echoes of the conflicting obligations and organizational divisions the authors saw in the BIM teams. Energy models themselves are complex integrated datasets from four disciplines in that there are variables related to climate, architectural systems (e.g., exterior cladding), mechanical systems (e.g., heating and cooling) as well as building user and operational factors (e.g., operating hours, heating set points). Like in the BIM teams, the energy modeling analysis worked best when the disciplinary experts, whose work was represented in the energy model, worked closely together to develop and then refine the energy model: their analysis was more meaningful to the designers and helped the team make decisions about architectural, mechanical and building operations choices. In other words, when the architects, mechanical engineers, and owner representatives recognized the constructed nature of the energy model—that the model was not a snap shot of the design, but an analytical tool to vet and test alternatives—the results were more deeply integrated into design decision-making. The work of this integrated process included face-to-face meetings where owner representatives, architects, and engineers met to work through design options and leverage energy modeling and design visualization tools to assess the implications of these choices together.

Strategies to Contextual Challenges

During this research, the authors found four mechanisms that helped teams overcome organizational and technical project challenges. The authors found that leadership was one of the main mechanisms for project teams to deal with conflicting obligations. For the isolated MEP teams, leadership was the one organizational mechanism these teams had to work through their conflicting obligations and the loosely-coupled organization of their project. When leadership was not sufficient, MEP team members retreated to protect their own scope of work and their company. In contrast to the isolated MEP coordination teams, one of the BIM projects included representatives from the architecture and engineering firms on the project in the weekly coordination meetings. While the tighter organization supported interaction, leadership still played an important role in these teams to build team solidarity. Now that the organization mirrored the modeling tools—the expertise represented in the models including MEP systems, architecture, and structure—the conflicting obligations were more balanced and managed as MEP detailers could articulate their concerns and these concerns were addressed by the group. In some cases, MEP detailers encouraged others to “do what is best for the project.” Based on this research, the authors argue that building coordination requires the work of experts to come together to coordinate their systems, supported by information technologies (e.g., BIMs) that help them understand and communicate the interrelationships between their systems.

In the energy modeling work, the authors saw a similar pattern of success when the organizational form of the team mirrored the data requirements from the technology. What emerged from this line of research was the importance of the owner organization to the overall building design and performance (Dossick et al., 2016; Monson et al., 2016). The efforts to improve building energy performance make the owner, end users, and operations more central in the design process. In all projects, the owner played an important role of setting design aspirations and goals of the project. These goals were interpreted and championed by the design and construction leadership and enacted by project team members. The authors found that when energy performance specifically and building performance in general was a part of the project’s aspirations, the owner had a more active role in the design process as they have technical knowledge about the use and users of the facility that is key to achieving the design outcome. In terms of energy modeling, building user and operator assumptions are part of the “data” that is used in the software, and therefore makes the owner one of the disciplinary experts needed for model development.

Once the organization of experts were brought together around their models and documents, the research team analyzed the ways in which these multidisciplinary teams interacted with each other using their data. In watching design and construction team interactions, the research team defined the interdisciplinary knowledge work as “messy talk” (Dossick & Neff, 2010). In the AEC teams observed, interaction was *messy* in that it was unscripted, where ideas and new solutions were emergent from interdisciplinary dialogue. Individuals would come in with questions for each other and issues to address in the design or construction process. As the team began to discuss these issues, other questions emerged and discoveries were made. Often the team was vetting design proposals where the team would explore new system options or routing alternatives. In

this exploration, they would exchange their disciplinary knowledge and critically engage each other through questions about technical details, such as building systems or codes. The value of this process was articulated as one team came up with a solution that resolved the constraints of running electrical systems through sensitive lab areas. During this exchange around the solution, the subcontractor reflected, “Why didn't I think of that?” The architect responded, “Sometimes you need to talk it through with others.” In this research, the authors observed that this messy talk was not supported by the information technologies the teams were using. Their projections of coordinated 3D Models (BIM) did not support the quick moving knowledge work for “spit balling” ideas. For messy talk, teams used flexible and malleable mediums such as white boards and paper-based drawings. They also used abstracted visualizations to support messy talk interaction, which brings us to the next concept: interpretive flexibility.

The introduction of BIM (highly detailed 3D visualizations) resulted in the ability to create and analyze building systems in early phases of design. While this is valuable for design and construction teams to discover constraints and issues earlier in the process when it is more efficient to make course corrections, highly detailed visualizations were also in conflict with design work and messy talk interactions where visualization authors would intentionally create abstract representations of building systems. Even in later stages of MEP coordination, the authors watched teams draw abstract representations on white boards to work through new design ideas. In this research, the authors used the idea of interpretive flexibility to explore these knowledge work requirements. Unlike detailed 3D models, abstract representation in 2D plan or elevation views allowed team members to imagine alternative solutions. They could quickly sketch ideas through the abstracted floor plan and mentally vet the ramifications of that sketch. When the teams hit a conflict, they could then erase that idea and draw another option to consider. Essentially, what the authors theorized was that to support messy talk and ideation, teams needed visualizations with interpretive flexibility (Dossick & Neff, 2014). While higher detailed models and analysis helped them understand the implications of design proposals, the teams still needed abstract representations to support design ideation. In Part II, the authors review how even distributed teams and virtual worlds mirrored the same need for multiple methods of visualization and the need to intentionally curate spaces for team interaction in order to make their data and expertise meaningful to others.

Part II - Distributed Teams and Virtual Worlds - the need for multiple media

This section discusses seven years of research studying globally distributed student teams as they collaborated online. The constellation of universities that participated varied from year to year. Each year at least four and sometimes as many as seven universities participated in a shared term project. Students in undergraduate and graduate levels worked together on BIM-based analysis of a building project. Each school had a different scope of work. One built 3D models, another created a 4D model, another did model-based estimating, while others did safety design, and so forth. The teams worked together synchronously in 3D virtual worlds where they could interact as avatars side by side with their models (Iorio et al., 2011). This research project developed one virtual world tool in Unity called the CyberGRID. In this virtual world, avatars represent users, student models

were imported into the virtual world, and the students also had “team boards” that allowed them to share their screens and draw together with digital pens. In some years, some of the student teams did not use the 3D virtual world and instead used screen sharing technology such as Sococo, Skype, and Google Hangout. This allowed the researchers to study distributed teams and compare a variety of collaboration tools to explore how virtual teams adapt these technologies to support their work. Namely, when team are mediated through technology and do not have the affordances of face-to-face interaction with mutable media, how do distributed virtual teams develop messy talk (Authors Cite)?

When watching teams in the CyberGRID environment, the authors observed that the distributed team interaction mirrored the interactions the authors saw in the face-to-face teams that the authors observed in the BIM and Energy modeling research discussed in Part I. Students would use their avatars to explore the model together, similar to how MEP coordination teams would navigate through a consolidated model together. The primary work these teams did in the avatar-model space was to discover issues with the model. It was not until the virtual team came back to the team board—where they projected a floor plan and began to sketch over the top of it with digital pens—that the Cybergrid team began to engage in messy talk interactions. This virtual team process was akin to the MEP coordination team process where the MEP coordination team turned off their projectors and smaller groups would huddle around white boards or paper to sketch out ideas and discuss possible design options. In both issue discovery and problem solving, the face-to-face teams and virtual teams leveraged their tools in analogous ways. That is to say, they used the models to discover issues in the design, while they used more flexible media for sketching and more abstract representations to propose and discuss new design options.

As the distributed team research was a quasi-experiment where researchers observed student teams working with distributed team technologies and saw the student teams experiment with the tools, the researchers could compare across platforms and modes of sharing visualizations. In one study from this project, when counting the number of instances the student teams discovered issues with their models, the research team found that the avatar-model space produced significantly more discoveries than the shared screen environments in both the CyberGRID setting as well as the screen sharing tools (Anderson, 2015). This finding was echoed in another virtual world study where industry experts compared the use of 4D models in emerged virtual world environments with viewing 4D models on a shared screen. In the 4D model study, Pratama (2015) found that when in the immersive environment users tended to want to go inside the building to watch the 4D simulation from the first person viewpoint, while the experts who watched the 4D simulation on a shared screen would stay outside of the building, watching the model from a bird's eye view (Pratama 2015). Both of these studies suggest that different views and interfaces with modeling data support different types of knowledge work. In the Anderson (2015) study students used the avatar-model space to discover issues, and used the team wall to generate solutions. In the Pratama (2015) study, the immersive system allowed experts to see the 4D simulation from the first person point of view, while the shared screen encouraged team members to see and discuss together the overall simulation model. Consequently, in this paper, the authors argue that the modeling technologies available today supplement more traditional visualization tools for AEC

teams. In other words, all of the different types of visualizations—2D and 3D—have a useful purpose for the knowledge work of AEC teams. What both the BIM/energy modeling research and the distributed virtual team research suggest is that AEC teams need flexible, malleable media and abstract representations for messy talk, as well as more highly detailed, complex 3D views for discovery and understanding.

As there are uses for the variety of visualizations available to AEC teams, there is a need to intentionally curate spaces and visualizations for team interaction. Managers and modelers need to spend time thinking about the type of knowledge work that they seek to support, and then create and tailor visualizations to support this work. Does the team need first person or bird's eye viewpoints? Does the team need abstract representations and flexible malleable media for messy talk interactions? Do they need shared screen views and/or independent viewpoints? What this research has found is that for discovery, independent first-person viewpoints are extremely effective. In addition, the team is productive as they are exploring the space together (Anderson, 2015). These studies suggest that the ability to toggle between first-person viewpoint and shared viewpoint would be advantageous, as the team osculates between finding issues and created a shared understanding of them. This research leads the authors to argue that there is a need for teams to intentionally curate visualizations and interactions that support the knowledge work they seek to do whether working face-to-face with their team members, or working in a digitally mediated distributed environment. As the industry introduces virtual reality and augmented reality technologies, these findings will be important as technologists design systems for interaction. Namely, if designers are seeking to discover issues in the design, the first person viewpoint is best, and if they seek to vet design alternatives, a more flexible medium with more abstract representations supports this messy interaction.

Part III - Information Exchange and the work of making data work

While Part I and II focused on how teams organize and visualize in ways that make data meaningful to team members from other disciplines and firms—making more holistic design and construction decisions in the process—, Part III reviews research on the often-unseen human labor involved in making data usable for other applications. In other words, how people innovate processes in order to make data meaningful to other operating systems. This section covers five years of research efforts looking at the challenges of interoperability and information exchange in BIM to Facilities Management (FM). Interoperability challenges in BIM to FM are due to a lack of data standards across BIM and FM technologies (Kassem et al., 2015; Volk et al., 2014), diverse software tools (Becerik-Gerber et al., 2012), stakeholder organizational differences (Ilter and Ergen, 2015), and inefficiencies, including the need to manually reenter data into FM software (Gallaher, et al., 2004). These challenges come at a high cost to owners and contractors and often require extensive financial resources (Kasprzak and Dubler, 2012): something end users of FM systems often do not anticipate during the earlier stages of project design and construction. While there is an emerging view from owners that there is a need to prepare for the time, labor, and costs of information exchange (CERC, 2016), traditionally, owners have viewed the creation of “better tools” as the primary solution (Gallaher, et al., 2004).

In BIM to FM applied research projects, the authors were often tasked to work with industry collaborators and find efficient workflows to overcome information exchange challenges: to work towards a more seamless exchange of data to FM systems. During a project for USACE, the research team developed a workflow process that exchanged BIM data to an asset management system (AMS). This workflow involved data extraction from BIM, data integration (e.g., manually checking the extracted data to ensure it can be made useful for the AMS), and data mapping the integrated data (i.e., an automated or semi-automated process that maps BIM data types to AMS data types) into a format that the AMS could understand and use.

In lay terms, this process meant having to extract the BIM data from a Revit file, upload the data into a mapping software program that could transform the data into an interoperable database, and then extract the data out of program and upload it into the AMS. During this process, the authors encountered periods of what critical data studies scholars call, *breakdown*: moments when the authors would encounter the material limits of the data (Jackson, 2014; Tanweer et al., 2016). This occurred when the extracted data file from Revit would not automatically fit the data requirements of the mapping software program, and when the authors had to manually map asset data (e.g., AMS identification codes) to each data point to uploading the data into the mapping software.

These moments of breakdown led to the need to *repair* the data (Tanweer et al., 2016). This repair work generated technical and organizational work process innovations that were key not only for this research team's information exchange efforts, but to the future work processes of data users in our collaborator's organization. One key process innovation during repair was the development of *Codemapper*: a custom-made Excel spreadsheet that helped to automate the data extraction and "cleaning" process. As the research team's industry collaborator owned multiple facilities of the same type, this spreadsheet also provided the opportunity for future users to automate the mapping process of the workflow: once a user manually mapped one type of facility, they could automate mapping of facilities of the same type.

This process of breakdown and repair highlights how work is required to condition data for useful and meaningful exchange between technical systems. It is work that leads to process innovations. Through these processes where people work with the materiality of data, the authors can see that data is not absolute: its constructed nature is part and parcel of both people and technologies, requiring effort to make data work across systems. The constructed nature of data connects with Part I of this paper in that if data is constructed, it requires the owners of this data to participate in the process of making and exchanging data. When dealing with repair processes, data authors and owners are best positioned to understand the data providence and structure and then create data extraction, cleaning and exchange processes. This is counter to the commonly held belief that data is absolute or agnostic and should be easily transferred and manipulated. Just as this paper argues in Part I that expertise is only *represented* in models, so to is data connected to the experts who create them. When data is extracted from the experts who created them, the contextual and structural knowledge is lost. Consequently, the utility of this data is limited by the uncertainty of quality and the capacity of the contents. As the industry designs new

information exchange processes, considerations around data authorship and participation of experts in the exchange process will be vital to the success of that data exchange. The ramifications of this research is that information exchange is as much about a handoff between data owners as it is a transfer of data from one database to another.

Conclusion

The introduction of technology into the design and planning of projects can, under the right conditions, support better communication and organization for project teams. The use of new information technologies often required design, construction and owner teams to work in new ways. BIM emerged at a time when design and construction teams needed strong leadership both to navigate the loose organizational structure of design and construction projects and to broker information in and out of the BIM team to the broader project team. Energy design teams also required new kinds of organization to leverage energy analysis—a boundary spanning leader who could help translate project goals into new modes of analytics and then help translate those results back into project designs. Both of these sets of professional teams often faced barriers to sharing their insights with key decision-makers and translating their analysis into the goals and designs for the project. In the distributed student teams, students found new ways of working outside of the BIM model, bringing sketching and multiple media into building models and data in the CyberGRID. These three streams of research teach us that that multidisciplinary teams designing together need malleable, flexible, and informal media, along with expert interactions and discussions, to coproduce knowledge. They also work best when the organization of the project teams can adapt to requirements for the new information system, whether that is bringing certain types of decision-making power into meetings or ensuring new kinds of boundary spanning leaders help connect data to goals to expertise to decisions.

This work suggests that AEC teams need to intentionally curate spaces and visualizations for team interaction. The “interpretive flexibility” of plans and drawings means that teams need multiple forms of media and representation to “see” and think through the ramifications of design proposals using the lens of their own disciplinary expertise and their knowledge of the project’s goals and constraints. As a result, models, information, and data require creative, resourceful, and inventive work to support visualization and knowledge exchange as well as data exchange. Project teams, leaders, and technologists should be strategic and intentional when setting up work places and systems for expert interaction and information exchange, because it is this interaction with other experts that is the key to making the models and data work for the project.

Models and data embody expert opinion and judgment. Data generated from design and construction technologies require configuration and verification to their use and reuse over the life cycle of a project. As the industry tries to leverage data from design through operations, experts work to convert datasets from one structure to another. These cases suggest that the data generated from models and analytics will continue to be useful, but that their integration should never be presumed to be seamless. Data will always require some kind of work to translate from one context to another, whether it is from architectural design to engineering design or from construction to operations. For the

industry this means that there is a need for intentional investment in both the social and technical interfaces of interaction around the exchange of data.

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