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DESIGN PRINCIPLES FOR IT IN DOUBLY DISTRIBUTED DESIGN NETWORKS[1]

Principes de conception des TIC dans des réseaux de conception doublement distribués

Completed Research Paper

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Abstract

Information systems research that focuses on design activity tends to emphasize (1) individual designer cognition, (2) data integration in a design context; or (3) social processes at the boundaries between communities in a design context. However, there is limited research into the distribution of design activity across both distributed designers and the heterogeneous technologies that are embedded in their practices _ across what we described as doubly distributed design networks. In our cross-case analysis of five doubly distributed design networks in the architecture, engineering, and construction (AEC) industry, we elicit six principles for the design of IT intended to support doubly distributed design network. From these principles we derive a set of theoretical propositions that question the applicability of the prevailing, single-model /unified infrastructure paradigm for such networks. Further, this research reconceptualizes the notion of design iteration in such contexts.

Résumé

A partir d'une analyse multi-cas de cinq réseaux de conception doublement distribués, nous obtenons six principes pour la conception de TIC visant à soutenir un tel type d'activité. Nous dégageons de ces principes des propositions qui questionnent l'applicabilité du modèle unique et du paradigme de l'infrastructure unifiée actuellement dominants.

Keywords: Doubly distributed; design networks; design principles; design infrastructures; design artifacts; design iterations; Design/design science, Innovation, Distributed work

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Introduction

Innovation is critical to organizational survival in today's knowledge economy, and designers charged with the creation of innovations rely upon information technologies for their work. While there has recently been an increased focus on the ways information technologies support design activity across networks of designers (Boland et al 2007, Carlile 2002, Thomke 2006), and work related to principles for the creation of technological artifacts to support this type of work (e.g., Bergman et al 2007; Avital & Te'eni 2008; Markus et al 2002), there has been limited research to date focusing on specifically on doubly distributed (Yoo et al 2008) design networks. "Doubly distributed" refers to design activity that is dispersed across both diverse knowledge sources and heterogeneous technological resources (Yoo et al., 2008). Such networks are becoming more prevalent as innovative design activity is increasingly distributed across diverse contexts (Tuomi 2002; von Hippel 2005; Majchrzak et al 2000). In this research, we look to identify design principles which can guide the creation of new information infrastructures that go beyond the prevailing characterizations of design work to support doubly distributed design activity.

In organizational contexts, information systems are generally thought to facilitate communication and coordination among designers, enable designers to digitally visualize and experiment with design alternatives, and to manage both the design process and related data (Baba & Nobeoka 1998; Thomke 1998; Thomke 2006; Yassine et al 2004). The bulk of literature on information systems that support design emphasizes singular tools intended to support: (1) the cognitive activity of an individual designer (e.g., Baba & Nobeoka 1998), (2) for a number of designers as a shared representation (e.g., Yap et al 2003), or (3) as a centrally-controlled, integrated design infrastructure (e.g., Argyres 1999, or see the literature on CPC or PLM: Banker et al 2006 or Grieves 2006). Recent research on the information systems that designers use in highly innovative contexts, however, suggests that the prevailing emphasis on a single tool or a unified infrastructure may not accurately depict the dynamics associated with the appropriation of information technologies in highly innovative design activities (Boland et al 2007; Bailey et al 2007; Berente et al 2007). In these cases, designers work within ecologies of artifacts that include multiple varying information technologies (Bailey et al 2007; Bucciarelli 1994). As innovative design activity draws from different knowledge sources (Hughes 1987), diverse perspectives and technologies must continually be reconciled throughout the design process (Berente et al 2007). In addition to technologically-mediated and supported human communication, researchers find a great deal of human-mediation between the technologies that are embedded in their design activity (Bailey et al 2007). In such a context, networks of increasingly diverse (and geographically dispersed) actors forming a design network employ a multitude of federated, loosely coupled, and specialized information technologies in order to successfully innovate with designs. We refer to such contexts as *doubly distributed* design networks – those that exhibit distributed (socially and physically) control over innovation processes, and high degrees of heterogeneous technology artifacts - and we look to identify specific principles that can be used for the creation of information technology infrastructures that can support such networks.

We draw on the principles that Boland and associates (1994, Boland & Tenkasi 1995) relate to the creation of information technologies to support distributed cognitive activity such as designing. Such activity involves diverse designers – each with their own perspectives - interacting with a multiplicity of representations to both deepen their own perspectives and to communicate these perspectives with others. We extend this work to a context of doubly distributed design networks where diverse perspectives are invested in heterogeneous, often incompatible information technologies (Carlile 2002), and where design changes, or iterations, cascade across a variety of organizational actors and their technologies. The goal of this work is to theorize principles that can guide the creation of new forms of information technology to support doubly distributed design network.

We adopt a broader design science perspective (Gregor & Jones 2007) and focus on a specific domain within design activity to elicit principles as theory that can guide the creation of new artifacts. We perform a cross-case analysis of five different architecture, engineering, & construction (AEC) design contexts to ground our theoretical assertions in doubly distributed design activity. AEC projects provide an excellent opportunity to study dynamic, diverse project teams, as they involve multiple specialist communities coming together, and these communities often leverage distinct ecologies of technological artifacts. AEC projects involve communities such as architects, owners, a variety of engineers (structural, civil, etc.), surveyors, and fabricators (structural steel, sheet metal, glass, etc.), among others. Furthermore, novel AEC projects are always unique, providing ideal contexts to study the managerial challenges for companies that are required to deal with increasingly customized and complex design activities.

The remainder of this paper is organized as follows: first we briefly review the literature on information technologies that support design activity, introduce the notion of doubly distributed design networks, and present our research questions. Then we describe five vignettes from our data to illustrate the six emergent design principles in doubly distributed design contexts. We conclude by extending the Boland et al (1994) principles for designing such doubly distributed design networks. Using these principles, we derive a set of theoretical propositions related to more effective generation of design innovations in such contexts.

Design and Information Technology

By design, we refer to the activity concerned with intentionally transforming existing situations into desired ones (Simon 1996). Throughout this activity, designers must learn about both the existing and desired situations, as well as the basis upon which desired situations will be judged (Churchman 1971). In support of learning, the fundamental unit of design activity is iteration: generate-test cycles where design alternatives are created and tested to aid designers in learning about both the problem and its solution (i.e., navigating both the problem space and solution space, Simon 1996; Dorst & Cross 2001).

The bulk of the classic literature on design emphasizes cognitive activity of *individual* designers, often through a designer's interaction with representational artifacts (e.g. Simon 1996; Churchman 1971; Alexander 1979; Cross 1994; Checkland 1981). Individual design activity is based on a form of abductive reasoning, which involves the generation and testing of design hypotheses (i.e., educated "guesses," Peirce 1992) using representational artifacts. Designers leverage models, drawings, and other artifacts to capture elements of design hypotheses, and then test these hypotheses through inspection or analysis, and modify hypotheses as they move along the design path. The testing of design models takes the form of hermeneutic inquiry, where a designer's reflections cycle between parts and the whole of the design and its context (Snodgrass & Coyne 1992; Checkland 1981). Accordingly, a bulk of the research that looks into information systems that support design activity emphasizes, at least implicitly, the activity of individual designers. For example, in their work on "emerging knowledge processes," Markus and associates (2002) emphasized the ways in which expert design knowledge can be codified and used by individuals interacting with an IT artifact, as well as technical features of such technologies. In another study, Avital & Te'eni (2008) described the principles associated with IT artifacts that can enhance the capacity of individuals to discover, be creative, and generate novelty in design.

This focus on the individual, however, only captures a portion of design activity. Especially in complex design projects, design activity occurs across many individuals distributed within a single organization or across organizations. Much of the literature on IT and distributed design activity has its roots in product design and development research (Ulrich & Eppinger 1995) which has generally focused on the merits IT design infrastructures that enable data integration (Malone et al 1987). Information systems in this stream are expected to facilitate communication and coordination among designers, which enables designers to manage the design processes and design data (Baba & Nobeoka 1998; Thomke 1998; Thomke 2006; Yassine et al 2004; Ulrich & Eppinger 1995). Not surprisingly, this stream therefore characterizes IT as singular, centrally-controlled, and integrated design infrastructure that will support all design activity across a network (e.g., CPC or PLM: Banker et al 2006; Bardhan 2007; Grieves 2006; Stark 2005). The key prescription for implementing information technology in support of distributed design within the PDD discourse is thus to centrally integrate design tools across groups (Thomke 2006).

It is important to recognize, however, that the distributed design occurs across disparate knowledge communities, and involves a critical social dimension: diverse knowledge sources must be leveraged to effectively engage in complex design (Dougherty 1992; Boland & Tenkasi 1995; Carlile 2002). In such contexts, multiple representational artifacts are iteratively appropriated both in conjunction with individual cognition, but also in communication and coordination with others (Perry & Sanderson 1998; Boland et al 1994; Berente & Lyytinen 2005). Design activity must traverse syntactic, semantic, and pragmatic boundaries that exist between diverse groups (Carlile 2002). While syntactic boundaries can be readily addressed through information technology through gateways and transformers, semantic boundaries that involve local interpretation, tend to be problematic (Dougherty 1992; Boland & Tenkasi 1995). Further, knowledge and related interests are embedded in the practices of the disparate groups, creating pragmatic boundaries (Carlile 2002), which are overcome through conflict resolution, negotiation, dialog, and learning (Bucciarelli 1994). As rationalities of diverse groups are rooted in their disparate practices, design in general can be characterized as argumentation between different logical modalities (Buchanan 1992). Yet, these social and political dimensions of design networks are not highlighted the mainstream of the PDD discourse (for an exception, see Clark & Fujimoto 1991).

To aid in navigating semantic and pragmatic boundaries, information technology is often conceived as a design boundary object (Star & Griesemer 1989; Henderson 1991, Bergman et al 2007) that mediates group interactions, enabling them to cut across boundaries through transferring data, translating meaning, and transforming and legitimizing design knowledge (Carlile 2004, Bergman et al 2007). The presence of such design boundary objects does not imply that diverse communities somehow become "homogenized" (Kellogg et al 2006) in their IT usage or their design perspectives. Instead, each group is implicated in its own "technological trajectory," that remains loosely coupled with the practices of other groups through "trading zones" by which design groups coordinate activity and exchange design perspectives, knowledge, etc. (Boland et al 2007). Each of the disparate groups maintains *their* ecologies of representations and technological artifacts that are embedded in their work to support their unique forms of knowledge (Bucciarelli 1994; Carlile 2004).

Research targeted toward eliciting principles of IT artifacts that support design as distributed social activity, albeit sparse, does exist. For example, both Bergman and associates (2007) and Carlile (2004) characterize the principles of information technologies that act as effective design boundary objects to embody a shared language, to offer practical means for learning across groups, and to facilitate joint knowledge creation and legitimization. In another example Boland and associates (1994) described a design science project for a system intended to support distributed hermeneutic inquiry, and they indicated that such a system should allow for indeterminacy of the design, as well as nurture a multiplicity of diverse actors, representational forms, and interpretations. However, this existing research on social aspects of design activity tends to focus on information technologies at the boundaries. This research does not call attention for the need to bridge the technologies that are embedded in the practices of these different communities (Bailey et al 2007), nor for the set of cascading changes to both technologies and practices that ripple across design networks with the introduction of new technologies at existing boundaries or across new boundaries (Boland et al 2007). These observations invite a richer conceptualization of the relationships between diverse information technologies as well as their diverse communities.

Doubly Distributed Design Networks

Based on our review of the literature, we observe that much of the IS research on design activity tends to focus on (1) individual design cognition, (2) the merits of data (syntactic) integration in a design context; or (3) the role of IT in mediating social processes at the boundaries in a design context. There is a gap in design theorizing that involves the socio-technical distribution of design activity across *both* distributed designers *and* the heterogeneous technologies that are embedded in their practices – what we refer to as *doubly distributed design networks*.

To examine these doubly distributed design networks, we draw on the work of Boland and associates (1994; Boland & Tenkasi 1995). We chose this as a starting point, because it represents an early design science project where the main purpose of the project was the creation of an IT artifact intended to support distributed design, and because its theoretical lens explicitly attends to the three aspects of IT and design we have identified: 1) supporting individual cognition, 2) as an integrated platform, and 3) in mediating social processes. Designers use artifacts to codify aspects of individual perspectives about the design, thus enabling them to reflect on their designs, but also to communicate the design information, and to mediate the sharing of perspectives (Boland & Tenkasi 1995). In addition, the principles have been empirically tested and validated (Majchrzak et al 2005)[2].

Boland and associates (1994) elicit six principles for the creation of artifacts to support distributed design activity: multiplicity, mixed form, ownership, easy travel, indeterminacy, and emergence. The principle of "multiplicity" refers to the multiple actors and multiple representations (of the same type) associated with distributed design activity; "mixed forms" addresses the variety of different representational types that can be appropriated; and "ownership" describes the need for an IT artifact to associate these representations with the appropriate individuals. "Indeterminacy" describes tentative nature of any representation and highlights the way in which no single representation can be comprehensive and precise along every conceivable dimension. "Easy travel" describes the need for linkages between parts of a design, or between parts and the whole, to enable ready navigation across complex designs, and "emergence" describes the need to accommodate the synthesis of part relationships into wholes, thus to address higher level, emergent, issues.

While this set of principles may be comprehensive for the ways that IT artifacts are generally conceived, it does not directly address many of the issues that are central to doubly distributed networks. Although the diversity of

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[2] In addition to their empirical validation of the principles, Majchrzak et al (2005) indicate that there was preliminary, qualitative support for these principles in two previous studies (Majchrzak et al. 2000, Malhotra et al. 2001); further, the "general philosophy" behind these principles has been validated by Ackerman et al through their extensive work on "Answer Garden" software (see: Ackerman & McDonald 1996).

individuals and representations associated with innovative design work is a central concern, the heterogeneity of artifacts *outside* of the shared artifact and the need to reconcile multiple representations that are not embodied in the shared artifact remains a key concern. While earlier studies address a given artifact or set of artifacts as they are utilized during a design process, no work to date has addressed the organization of doubly distributed design practices. Further, as the synchronization of design actions and reconciliation of multiple perspectives is fundamental to group design (Valkenberg & Dorst 1998), it is important to focus on the way design changes, or iterations, are addressed across *both* social and technological domains in a doubly distributed design activity.

Therefore, we next examine doubly distributed design activity *in situ* to gain insights into the following questions:

1. What are the ways that individuals appropriate and navigate information technology artifacts in a doubly distributed design network? How is this different from the way design is typically characterized?
2. What are the limitations of existing information technologies in supporting such design practices?
3. Based on an analysis of doubly distributed design networks can the six principles for IT that supports distributed design (Boland et al 1994) be refined and extended for such contexts?

Research Method

We conducted inductive data analysis to generate a theory on the design and the appropriation of information technologies in doubly distributed design networks. Following Eisenhardt (1989), we use cross-case analyses for theory generation. We leverage the data from thirty-eight interviews that were conducted over a twelve-month period across five architectural design projects in the AEC industry. This data collection forms a part of an on-going field study which involves dozens of different organizations from various trades in AEC over multiple years.

Due to space limitations, instead of presenting full case studies we present concise vignettes from our field work that highlight social and technical challenges in five architectural projects. Due to the distributed nature of the control and the involvements of multitude of different trades, the AEC industry presents an ideal context for the study of doubly distributed design networks. Following Eisenhardt, we developed a systematic research protocol that guides our data collection in the field and focuses the research team on how digital tools are appropriated in design setting. The protocol employs open-ended questions crafted to assess the individual and collaborative practices of designers, especially with regard to design changes, across the design network. Interviews were recorded and transcribed. From this data, we engaged in "within-case analysis" and generated detailed write-ups of each case study. We engaged in comparative analysis of the cases for inductive pattern discovery and matching for theory generation. The project team employs an on-line research database (Yin 2003) that organizes audio files, transcriptions, images, and documents to support our own distributed collaboration.

Findings

Our analysis of the five cases highlighted the importance of understanding changes to the design in shaping design activity across doubly distributed design networks. Many new, extended, or changed design representations set off a wave of cascading changes across the design network. These changes, in turn, set off their own changes across multiple different representations, through a variety of different information technologies, and across a variety of groups and specialties within the network. Also, these changes did not occur in a recurring pattern. Designers managed different changes using different ecologies of representations, even when they were distributed across the same actors.

Through our analysis of the data, we observed six principles from design activities that managed changes across the doubly distributed network:

- We named the first principle "semantic coherence" to describe the finding that, although groups used different (often incompatible) representations and leveraged different IT artifacts, it was not enough to merely identify the different views of the design, but these views had to be *semantically* reconciled.
- The next principle was "synchronization," just as certain teams "synchronize their watches" in order to effectively coordinate timed activities, because of the constant stream of changes, doubly distributed design teams periodically communicate the design representations as they stand at a moment in time to synchronize the "state of the moment" of a design project.

- Further, we identify the principle of “representational flexibility” to emphasize not only the variety of representations used by designers, but how these representations are both generated and communicated in a situated manner – unique ecologies of representations are used to manage different design changes idiosyncratically within and across different pockets of the network.
- The principle of “regenerativity” highlights the need for designers to recreate complicated design geometries in order to effectively understand aspects of the design – mere inspection of geometry across multiple representations and the related documentation is not enough.
- We point to the principle of “temporal traceability” to indicate the need for designers to interactively step through historical decisions in order to understand the current state of the design.
- Finally, we elicited the principle of “spatial traceability” to describe how designers traverse a variety of disparate representations about the design at a given moment. Although on the surface different aspects of the design and project documentation may seem unrelated, designers regularly had to cross-sectionally traverse and reconcile these disparate artifacts to understand the emergent design.

Next we will present vignettes from the five cases to illustrate each of these principles (names are pseudonyms).

John & the Commuter Station: *Semantic Coherence & Synchronization*

John is the associated architect for a large project related to Commuter Station. He is responsible for designing the covering structure (roof) for the commuter station in major metropolitan area. The covering is at street level and sits on top of the concrete box that houses the commuter station. There is a large air-recycling system that projects through the covering structure and into the concrete box that houses the commuter station. In addition there are complex and innovative electrical and wiring system related to the commuter train, the recycling system, and the other aspects of the commuter station. Furthermore, the design of the commuter station is tightly linked to the roads and local transportation systems that surround the structure. Thus a variety of adjacent changes impact the design of this covering structure, including: the box, air piping, electrical work, and road designs.

The models for the covering structure that John designs interact with other models that exist in the project. He uses Rhino, a 3D modeling tool, to develop the cover/roofing and this model works alongside with 2D models developed as part of the other contracts in the project and acts as a central model through which he identifies problems (similar to the role of the model in the vignette of Museum below). He notes:

“We have the whole structural box in Rhino. A lot of times the structural engineer needs to coordinate [with us] because we've set up all the geometries. He's got geometries. The priority geometries come from the rail lines. So those are established and then he has geometries and we have geometries that we have to maintain. So we have everything modeled in Rhino… So we collect everyone's independent little study and we have it in one place and we can begin to look at coordination issues if there's any interferences or anything like that.”

John coordinates building-related geometry from the different sources using his 3D model. However, this project is different because it involves a great deal of civil engineering, as well:

“*Typically on a building, you have property and you control your own property. Here, it's not your property. You've got to give right of way. So you're working with the city; you're working with major utilities; you're working with property owners. They all have their different criteria."*

One of the major challenges that John faced in this project is the different scales and measurement systems that civil engineers use for their portion of the work in the project. Different civil engineers and related contractors have different understanding of the same geography and the handoff's between portions of adjacent work was problematic and inconsistent. In a discussion with John and another project participant, Mark, they pointed out how 2D drawings from two different groups of civil engineers – the train engineers, who measure everything from the track – and the street engineers, who measure everything from a street centerline. As John recalls:

"There's no orthogonal grid [for train engineers]; everything is related to track. When the track curves, the coordinates curve, the origins curve. Everything follows track… Then I realized that the street engineers that have their own grid that's the center line of street. Their station points don't have anything to do with the rail station points. If this is the center line of the rail, here you can see the center line of the street up above. You can see the same station points, but these station points are related to the street. They have nothing to do with the rail.”

Further, both the train and street engineers periodically plot cross-sectional drawings of the design in no standard increments. According to Mark, "*They do sections generally every fifty feet or every twenty-five feet or something depending on what's going on in that particular area.*" This, in turn, exacerbates coordination problems.

To resolve this coordination problem John and the other participants perform a "stop and plot." They freeze the design process and share their models with each other and ensure that the coordinate axes employed with each other represent the same physical space. Individuals share the drawings generated by the different trades and coordinate their cognitive understanding of the physical space.

The vignette illustrates the need not only to coordinate different representations of the model, but to reconcile these representations across both the design information (geometries) and the point, or location in disparate representations ("stop and plot").

Stephanie and the Winery Project: *Representational Flexibility*

Stephanie is a structural engineer on an innovative winery design project, and is involved in the analysis for the roofing structure of the winery. The roof structure, described as a "trellis," is made from glass and wood and involves complicated, novel curves. This makes the project a complex undertaking as it requires imposing unique designs on materials that were not readily suitable for such purposes.

The design originated from the architect who developed a model of the trellis structure using Digital Project, a 3D tool, as it can develop the complex geometry required for such buildings. Stephanie directly receives Digital Project models from the architect's organization, and her role is to analyze the current model using analysis software to check for structural integrity. She notes:

"The architects use the Digital Project... So they use that to create their models. They also have a physical model too. I think they digitize. That's what they do. I think they start with the physical model and they scan the points on that thing which brings it into Digital Project, the 3-D modeling software. In there, they can label everything as far as what the different members are and everything like that. Every couple of weeks or at every predetermined stage, they send out their updated model which has changed a lot over the course of the project so far. "

She receives different versions of the model from the architect – for small changes she may receive just a small section of the design, but for big changes she might receive the whole model. The architect sends section models to Stephanie attached to an email, but for the large, complete models he load the model on an FTP site and informs her via email that a new model has been uploaded. Stephanie uses Digital Project to open the model and saves it in a format so that she can open it using Rhino, a tool that she is more comfortable with. This transformed version is a wireframe model that replaces curves in a series of straight lines and does not have surfaces present. She imports this newly constructed wireframe model to her analysis tool, Risa3D. The reason for the transformation (into a series of straight lines) is because the primary structural analysis tool, Risa3D, cannot handle curves. She points out how she needs a different tool than the architects to perform her work:

"So Digital Project itself is not a structural software at all. It's just for aesthetics; you just look at it. It will tell you distances between things but it won't do the structural part that we want to do. I have to then take the wireframe from that and then import it into RISA which is our structural analysis program, apply the loads in there, assign the member properties in there. Everything is in RISA like the member properties, if it's wood or if it's steel."

Stephanie performs a structural analysis of the structure in this tool and subsequently communicates back results to the architect. She explains:

"Then I analyze it in there [Risa]. It will tell me if this particular column is too small. Or that beam is too small or two big or whatever. Then I go back in [Digital Project]. What I've been doing right now is in Digital Project, there's a way to save a view and markup on it. You can just mark up like move this column here…Then I think about it and analyze and interpret the results that I get from RISA. What I've been doing is if I say, "Move this column here," then I'll physically move it in my RISA model to see if it really helps. So I'll move the column to where I think it will help the results and verify that it will help. I'll look at it and say, "Oh, it does help that particular area." Then I'll reflect that comment into Digital Project and say, "Move this column, because it will help."

However changes in the design also involve changes in materials used in the construction. In addition to two different alternatives of using bended wood, the architect also considered a new hybrid material that combines wood and concrete for the roof. This material is new development and its structural properties are not completely known. Stephanie communicates with engineers at the manufacturer of the material to get information about its structural properties she needs to complete her analysis. However, the manufacturer engineers do not always have information that Stephanie needs and subsequently run tests on the material to determine specific structural characteristics. Based on the analysis of materials and new designs Stephanie communicates changes and suggestions back to the architect. She notes:

"[The architects] come up with the ideas and then they bounce them off of us and they ask us how it affects us structurally. We've been doing research. I went down to LA to meet with the manufacturer to talk with him about structural properties and everything. We've actually been getting testing results from them to see if it's comparable to wood if not better or how it compares as a material property…Once we figure out how far that stuff can span, then we'll know where to put everything underneath it to hold it up. ….I've assumed a distance that this stuff can span. Once we get the testing back, we'll be able to verify that it actually can go that far."

Stephanie also interacts with engineers working on connecting the different types of materials, including glass, wood, steel, concrete and new hybrid material. These connector engineers are just getting involved in the project and will provide her with information about the structural capabilities of the connectors that she needs to verify will bear the required loads and stresses. She observes:

"There are a lot of different people that I think are going to be involved…. because they're still choosing between the materials and then all the connection between the two..I think when we talk with whoever they get onboard for the wood curving gluelam beams, they'll be able to tell us typical ways that they connect."

Stephanie communicates changes back to the architect in several ways. If the changes to the model are minor she communicates them via e-mail. If the changes are major she typically modifies the Digital Project model and adds annotations to the model, uploads it on the server and communicates the information about the changes to the architect. At times to explain the structural aspects of the model, she might also take screen shots of the tools she works in to communicate changes to the architect:

"Sometimes, or you can take this graph, like print the screen and say like you have a problem here, there's way too much deflection. Or like this member is not good. Or something like that. Usually this is for more internal. Like we use this to actually calculate the stuff, and then the results from this we actually tell the architect what's wrong."

This vignette highlights the multiple, typically highly tentative design representations that are used in the design communication. There is no single standard way of representing change, even if the general ecology of artifacts remains the same. Further, new actors (such as the manufacturer and connector engineers) are often enrolled in the project, often temporarily. Sometimes the communication involves partial models via email, screen shots of analysis findings, phone calls, 3D models, or marked-up models. Stephanie's feedback to the architect varies based on her anticipation of their information needs.

Suzy and Michael and the Gallery Project: *Regenerativity*

Suzy is an engineer on the Gallery project that works closely with the primary architects, steel contractors, wiring engineers and other participants, including Michael who works with her in the same structural engineering company. Michael – who is an expert on Catia with strong architecture and engineering background – often moves across projects in the organization as his skills and talents are needed. On the Gallery Project, Suzy works with two architectural firms – the primary and associate architects - to determine structural requirements for the project.

The primary architect is known for using complex geometry in his buildings and uses Rhino, a 3D design tool for digital building designs. The associate architect converts the Rhino model into a Revit model – a popular building information (BIM) system, an integrated IT infrastructure for AEC industry, and the official platform for the project. The associate architect then circulates the Revit model to the subcontractors for subsequent analysis processes. The primary architect saw the Gallery Project as an opportunity to learn about Revit which is increasingly popular in the industry. Suzy and Michael consider this as an unusual move but went along with this process since they and other participants in this project were also very interested in learning about the underlying technology behind this Revit.

Suzy: The lead architect is … very comfortable with Rhino. They weren't too sure about Revit, but they wanted to try it. They still want to make sure that the dimension of control is done in Rhino.

Michael: It was kind of like a push to go inside this Revit world and let's see how really helpful it is. That was definitely a good idea I think.

While the other subcontractors used the tool preferred by the associate architect, they also used tools that were part of their unique specialization. For example, the steel fabricator performed an analysis in their preferred tool, Tekla.

In the wake of a major design change started by the architect, this subcontractor discovered what they described to Suzy and Michael as *"a few things that don't correspond"* and asked them to *"please check… do you need a concrete cover over your bolts?"* Michael recalled the situation:

"…they are extremely prepared because I'm sure they found those kinds of problems in the field when it's too late. With this strange and unconventional building, they make sure that everybody's aware of a potential problem. This was not a potential problem, it was a big one. He said to me, "Michael, I found the one, two, and three columns. Maybe you want to check back with [another subcontractor] to make sure there is a column underneath." "Okay, so why don't you send me whatever base plate you have and let me check something."

Michael credits the steel fabricator with detection and avoidance of problems in the field. It was through their meticulous attention to detail, in conjunction with the Tekla software, that enabled them to find the problems:

"*Then they show us Tekla Structures. Tekla Structures is a 3-D model that is a very, very sophisticated and customized to a steel fabricator contractor. … It has no free form shapes. It has no surfaces. It has to be a beam. It has to be a real steel piece. What's happening is he's importing out of my model the surface and the wireframe of each steel member. He's using the wireframe to lay in a Tekla Structures the real steel section and extruding back again to match my surface. So he's sure that his shape is correct. When it's not he says, "Hey Michael, in your model it looks a W14 but in your drawing, there is W12. Which one?" "Oh I'm sorry, my mistake. The drawing needs to change because that was another thing." One by one by one by one. They are so particular and meticulous… Usually, all the problems are problems that you find in the field. Now, he wants to be sure that everything is ready to go. Buildings need to be built way before the real one.*

Michael subsequently took the models from the architect (Rhino Models), associate architect (Revit models) and specialized engineer (Tekla models) and converged them together to access consistency across the different model. Although all were 3D models, each one had some geometry that the others did not, and each looked at different aspects of the model, often at different levels of granularity. For example, the architect's model was highly detailed in external surface geometry, and the engineer's model involved highly detailed structural geometry. Michael convert Revit and Tekla models into Rhino models and superimposed them on top of each other. As he was not able to fully understand the model through this inspection, he created a new model in Rhino. Michael found a total of twelve problems with the design:

"I found twelve instead, not one, two, three only. Twelve! I sent this e-mail … everybody needs to see every possible correspondence. It was also to make sure that the strength of this alarm is good enough… Then they said, "One through twelve . . . One- this is the answer. Two- your Revit model doesn't show something but in the detail it shows that there is actually a notch that takes care of that. Three- . . . Four- please change your base plate." So in all twelve it turned out that one or two we needed to eventually take action ourselves ..."

This vignette illustrates the way in which different communities utilize specialized technologies. Beyond this, however, it highlights the limitations to the centralized integrated IT architecture in reconciling different models. Since each model has a different emphasis and a different level of granularity, and they are developed for specialized purposes, the problems with the models are not readily apparent through mere inspection. Rather, Michael had to recreate the full, combined model in order to understand the entire scope of the problem.

Kim and the Museum Project: *Temporal Traceability*

The museum project was already in the process of construction when Kim, a structural engineer, joined the project at the start of the "construction-documentation" phase. When she joined the project she was handed several 2D and 3D models from the previous structural engineer. The 3D models were Rhino models developed by the architect and the 2D models were developed by the steel detailer on the project. The architecture of the building has a complex roof geometry and since Kim inherited the models, she was unfamiliar with the specifics and was continually in the process of catching up. Since the project was entering construction, the models were continually being checked and several inconsistencies were identified. Kim notes:

"Well we actually had a big problem in this project where originally we did have this big model that had this framing … it had all of these wires too which were supposed to represent the locations of the second and third level beams. But what happened is that you know we had our 2-D drawings that showed all the beam sizes and locations on the second and third level and they weren't necessarily matching up. You know there were some minor conflicts between the two, maybe say this wire is supposed to be at nineteen foot four inches but it was at nineteen foot two inches and you know the steel detailer would get it and be like, "I don't get it. On the drawing it says nineteen foot

four, in this model it's nineteen foot two, and you know." So we got many, many, many RFIs (Requests for Information) and a lot of them had to do with just inconsistencies between 2-D documents and 3-D model."

Kim suggests that the presence of multiple types of representations led to inconsistencies between 2D and 3D representations. She further notes:

"So, like these are the plans you know, second and third level plans, everything is at the same elevation so we really, don't really need any 3-D model to define these. …. But at the roof, there's no way to really tell in 2-D what the curve is, where the location is. So we use that to define the geometry and then here we defined sizes, sizes of all the members. I think all these plans were just regular CAD things, that's how they were developed. We did develop a few in Rhino, things like this, this is our atrium - what we did is we basically took a screen shot in Rhino, imported it into CAD, and then drew in lines and then added information.

These inconsistencies in the two representations resulted in beams poking through surfaces. She recalls:

".. we ended up finding a bunch of places where beams were poking through surfaces and we would have to resolve that with [the architect's] office and creating sketches and details and reissue things. So there was probably like a two month period where a lot of, quite a few changes were still being made"

These inconsistencies created complications in the construction process and, although she had all of the models at her fingertips, Kim resolved the problem through continual RFI processes, phone calls, and web meetings with the other subcontractors and with the architect. She notes:

"Maybe at one point the previous engineer and the previous architect had caught all these things and it was on their long to-do list and it just never got done. We'd inherit the to-do list. There was sometimes I looked at the to-do list and I didn't know what they meant. This is incredibly explicit. "Beam at this gridline is too high. Raise so that it does not compete with ceiling." You just pick it up and you don't really know what that means. So I did inherit a to-do list, but there were some that I didn't know what it meant. Unless I sit there and just stare at the model and try to go through the whole process of comparing the drawings and the model, offsetting all the surfaces and all that, unless I did that, I wouldn't know that the problem was there.".

Kim had conversations and meetings with the participants on the project to resolve these inconsistencies. She works with the steel detailer, the general contractors and others in meetings at the site or through the use of web conferencing systems and phone calls. In addition to talking with others in the web conferences and phone calls she also works with the tools and models that the different parties use.

" I don't know if they have WebEx meetings for other topics but for structural steel we really need the model so that's why I use WebEx. … Like we'll always review shop models prior to shop drawings to make sure that the geometry is correct and also theoretically we find all the mistakes in the shop model then the shop drawings are almost, you know, it's just quick - we can send it right back. And so we'll usually give them comments and then the next week we'll go through all of them and make sure that, you know, [the steel detailer] understands what our comments are about and so they can ask questions if they still have problems. "

Although Kim received the complete information in the form of the different models, as well as the "to do" list, it was not enough for her to understand the problems and their histories. To resolve this lack of understanding, she requested a great deal of information "many, many, many RFIs" and engaged in continuous phone and web-based collaborative sessions. Since she came late into the project, she needed to spend a great deal of time getting up to speed with the design and its history.

This vignette illustrates the importance of temporal traceability in the design process and in design artifacts. As Kim moved through representations she had to rely on information handed down to her by previous structural engineers. This information is meaningful in the context where created and the fluid nature of design work required the reinterpretation of this information into the context of Kim's work as structural engineer.

Mike and the Convention Center: *Spatial Traceability*

Mike is a CAD operator for the general contracting organization of the Convention Center project. He is responsible for the 3D CAD models that are not part of the official documentation for this project, but are used as a "catch all" for the project, intended to reconcile various aspects of the design, scheduling, coordination and marketing process.

The structural steel engineers work with the project managers, construction managers, and site engineers to determine the process by which the building will be erected. Based on information received from the structural steel engineers, the erection plan gets finalized and Mike receives the scheduling information from the project scheduler. Mike then creates the 3D model by combining the different pieces of information together. The result is a 3D model with scheduling information built into it. This model is shared with all the sub-contractors on the project. He notes:

"Our project managers will have an idea of how they think the building needs to be erected. They will take that idea to the structural directors and get feedback from them and then of course have to tweak what their plan is from that. Then from there, once they get that information and they agree on that, then they'll bring it to me. Well, I guess they take it to Jim first so that he can incorporate it into the schedule and see how it's going to affect everything. Then they bring it to me to help create some sort of visualization that we can communicate with all the subcontractors. We have something nice and simple that everybody can hang up on their wall."

This model does not only contain scheduling information for the construction of the building but also information about how the construction interacts with the roads and other logistical issues at the site. Logistical issues can involve problems dealing with traffic around the site, the delivery of materials etc. Mike notes:

"Early on in the project, our superintendents and senior project managers will come up with how they want to organize the site to start off the building process… we look at the whole site and how it's going to be affected, where's we're going to set up and lay down, where everybody's going to work. So I will take the 2-D CAD drawings that we have of the site as well as get the structural [models] and incorporate them."

In putting in more detail for the scheduling and logistics and the 2D design, Mike needs the engineers to go out to the site and measure the points of the existing work that had already been done and as he starts to put this information into the model. He observes:

"Most of this vault was existing. Then we had stuff that had already been poured like our columns here and they weren't part of the design. So we had to have our field engineers go out there and actually shoot the points of the existing stuff … bring them to me, and I would take those points and draw this so that it was accurate."

In attempting to add detail to the model and keep it up to date Mike finds inconsistencies between the 2D drawings and the physical site. He recalls:

"From doing that, we've come to find out that a lot of these columns are too low. That was just part of the design. These here are storm drains. See that line there? That's how low this one was originally designed. On these 2-D printouts, you can kind of see what we went through. We did one first where we were showing discrepancies. Here you can see how low these are. That one comes up above the sidewalk a little bit, but then all these are too low. We just came up with a lot of issues like that. We'll try to come in here and cloud the different things. Then we even took the shop drawings from the subcontractors that were going to be installing the sidewalk, and I compared that as well and started finding discrepancies in that whether it will be dimensions or it's just not going to fit. This process went on for months and it's still not completely resolved."

This work by Mike resulted in flaws being found in the design and required a redesign of certain sections of the building by the architects on the project and changes the work done by the other subcontractors and the scheduling on the project. He further recalls:

"We've had to go through and redesign and show that we're going to raise these up. You're going to need additional concrete here, probably rebar as well. We also have some mechanical, plumbing, and stuff going through here, and you have to have access to them, so we're going to have a vent. That had to be coordinated with the precast guys so that before they build it, they know exactly where to put the spots that we have to have access."

Mike finds that the tools that he uses are incomplete and that he has to study the model in detail to determine the problems associated with it. He observes:

"What's interesting about this is a lot of the talk with the 3-D coordination process is collision detection. My software can do that as well and has in some instances where a couple of pieces of mechanical equipment will hit, and it will highlight that area where they hit. In this instance, it was the opposite. They weren't hitting; they weren't touching at all. You had to rotate and zoom it around and be like, "There's a big gap there." You just had to study it to figure it out. That's not going to work so then we'd have to get back in the details and make sure it was all drawn right. We kept verifying. That's what the details say, so we found flaws in the details by doing this."

This vignette reinforces ideas presented in other stories, such as the need to reconcile different representations, as well as learning about problems by recreating the geometry. The distinctive aspect of this vignette, however, is how Mike brought together data from disparate sources – in this case the scheduling and the modeling data – and linked aspects of geometry to the scheduling, and how design changes cascaded out through designs as well as through the schedule. The emergent new aspects of the design (combinations of schedule & geometry) were addressed by Mike through crossing the disparate models.

Discussion – Principles for IT in Doubly Distributed Design Networks

The presentation of our data intends to provide illustrative and typical examples of design activities in doubly distributed design networks that involves creation and changes to a variety of design artifacts. In each example, one or more of the principles associated with distributed design activity (Boland et al 1994) are evident, yet the implications that arise from them are qualitatively different. Where Boland and associates (1994) were looking to guide the design of an artifact or set of artifacts that can support distributed design, they did not allow for the heterogeneity of IT artifacts already embedded in the practices of the disparate communities, and the necessity to reconcile *both* perspectives *and* technologies. Therefore, we chose to rename the principles to better accommodate the doubly distributed nature of these design networks. In Table 1 below we summarize main observations, and we address briefly each principle in turn.

Table 1. Principles of IT for Doubly Distributed Design Networks

Distributed Design Principles Boland et al 1994	**Example**	**Case**	**Doubly Distributed Design Principles**
Ownership	3D Model used to reconcile variety of other models	Commuter Station / John (also Convention Center / Mike)	**Semantic coherence**
Multiplicity	Punctuation: "Stop and plot" synchronization; translate multiple coordinate systems	Commuter Station / John	**Synchronization**
Mixed forms	Situated ecology of representations; anticipation of representational needs	Winery / Stephanie	**Representational flexibility**
Easy travel	Learning by creating new model, different levels of detail found different number of errors	Gallery / Suzy and Michael (also Convention Center / Mike)	**Regenerativity**
Indeterminacy	Context: history of the design necessary to interpret design and changes	Museum / Kim	**Temporal traceability**
Emergence	Emergent, graphical schedule uncovered design issues that also impacted schedule	Convention Center / Mike	**Spatial traceability**

Semantic Coherence: The principle of *ownership* indicates that the representations of different design perspectives should be identifiable and associated with the individuals who hold those perspectives (Boland et al 1994). In the Commuter Station example we see how John uses the 3D Rhino system to reconcile a variety of representations from other, largely 2D sources (this is also evident in our vignette of the Convention Center). While the principle of ownership indicates that diverse representations must identify with their sources, our data indicates that in order to progress in design activity in a doubly distributed context, these competing representations must somehow be semantically reconciled together in a workable design.

Synchronization: The principle of *multiplicity* highlights the way multiple actors utilize different representations of the same design, with the implication that the same medium is used only the content of the design information is different across individuals, and for the same individual over time (Boland et al 1994). Our description of the Commuter Station project describes how different groups use 2D CAD systems to represent the data that is salient to them, and therefore contain different representations. However, we also find that these representations must be periodically synchronized in a punctuated fashion in order to progress with the design, as was the case with the periodic "stop and plot" activities. Further, our Commuter Station example illustrates the use of different coordinate systems among those 2D representations from the different trades, indicating that although the representations may be uniform in medium, the meanings associated with the representations require meta-level translations to adequately coordinate the coordinate systems (no pun intended here).

Representational Flexibility: Where *multiplicity* highlights the diverse representations of the content of a design (implying the same medium), the principle of *mixed forms* points to a diversity of forms of media – where multiple types of representations can be used to describe different aspects of potentially similar conceptualizations of the design (Boland et al 1994). In our analysis of the Winery Project, we find a variety of representations and media. Architects build both physical and digital models, and frequently change both of them, thus continuously sending Stephanie revised models. Stephanie, in return, sometimes sends marked-up models back, but also can send screen shots, revised models, simple notes, phone calls, or engage in collaborative WebEx sessions, depending on how she perceives the information needs of the architect. Thus we do see mixed forms of representation in Stephanie's individual work (i.e., Digital Project, wireframe, Risa3D), but we also see that she chooses to send a different ecology of representations depending on what she anticipates the information needs of the architects to be.

Regenerativity: By *easy travel*, Boland and associates (1994) describe the need to link parts of a design with other parts and with design wholes – so that one can "travel" through the design with ease. In our vignette from the Gallery Project, we found that Suzy and Michael were concerned with this issue as they attempted to navigate through three models with different geometries at different levels of detail. They ended up overlaying and essentially recreating a model to find the design problems. While the structural engineer, with limited part information found only three errors, Suzy and Michael found 12 errors while bringing the entire model together by linking its various parts and wholes. It is important to note, however, that they did not find these errors solely through inspection. Rather, they learned about the models by recreating again a new model.

Temporal Traceability: The principle of *indeterminacy* describes the need for tentative, equivocal, and imprecise representations in order to accommodate the development and sharing of partial perspectives during design (Boland et al 1994). What we found in the vignette from the Museum Project was the flip-side of indeterminacy, where even fairly well-documented design activities required a good deal of interpretation – an extra work on the part of Kim. Although all of the information about the design and the changes had been handed to her, Kim had to still request a great deal of information (RFIs) of the history of the design and design changes. In order to understand the strategic trajectory of the design, she had to understand the context of previous design decisions. She had to navigate the design history by tracing temporal patterns of change as to understand all the changes at any point in time.

Spatial Traceability: The principle of *emergence* indicates the need for designers to cycle between parts of the design and the emergent whole (hermeneutic cycle) as to understand it on higher levels (Boland et al 1994). In the convention center project, the emergent visualization associated with a 3D graphical schedule also ends up identifying design changes, which, in turn, sets off a series of representational changes that take a significant amount of time before revised data can be generated throughout the network and then used to create a newly revised schedule. The distributed aspects of these changes across the network are not fully appreciated in the concept of emergence. The locus of change is not at the point of identification, but in other parts of the network. The emanating path of the design change may begin and end with the graphical schedule, but it winds across the entire network. Therefore the emergent design changes must be traced cross-sectionally, or spatially, across the networks.

Together we critically expand the six original principles for distributed design (Boland et al 1994) to better accommodate the heterogeneous artifacts embedded in the practices of distributed and heterogeneous designers – or what we describe as doubly distributed design networks. Next, we will address these findings in an effort to generate propositions about the role IT infrastructures in the innovations from doubly distributed design networks, and to draw out implications of this work.

Discussion – Propositions and Implications

The fundamental purpose of doubly distributed design activity is the generation of complex innovations. Any effort to improve this activity using information technologies must first be sure that the process is as *effective* as it can be, that is, it must do what it is intended to do (Checkland 1981). Greater efficiencies across the design process do no good if the building comes crashing down, and it is a long-held axiom that improvements that shorten the overall design phase of a development project can have adverse implications in subsequent phases (Cohen et al 1996). This does not mean that efficiencies should be ignored, as streamlining design processes does often improve design outcomes, for example, by enabling more experimentation (Thomke 1998). However, it is important that these efficiency gains do not undermine effectiveness. Thus, to guide our propositions, the notion of the *effective generation of innovations* will serve as the key desired outcome (dependent variable) relating to doubly distributed design networks. Using this idea of effectiveness (Checkland 1981) we will discuss each of the principles we identified in comparison to the prevailing central, integrated infrastructure view, and put forth a set of propositions.

Through the principle of semantic coherence, we capture the spirit of the multiple meanings that require mediation from much of the distributed design literature that emphasizes boundary objects (e.g., Carlile 2002; Henderson 1991, Bergman et al 2007), but we do it in a way that does not require the interpenetrating infrastructure that implies homogenized practices across different communities. Instead, our characterization implies distinct artifacts within the trading zone between communities (Kellogg et al 2006; Boland et al 2007), that reconcile the different perspectives. This leads us to our first propositions:

P1a: Information systems that afford the reconciliation of representations from heterogeneous sources through semantic coherence will more effectively enable the generation of innovations across doubly distributed design networks than those that apply a single, standard model across diverse design communities.

P1b: Information systems that afford the reconciliation of representations from heterogeneous sources through semantic coherence will more effectively enable the generation of innovations across doubly distributed design networks than those based solely on separate representational forms for each design community.

Further, our principles of synchronization and representational flexibility highlight a multiplicity of representational forms that do not need to be reconciled semantically, but need to be reconciled along other dimensions. Every designer has a more-or-less unique design environment, or "object world" (Bucciarelli 1994), within which specialized IT artifacts are embedded and inextricable from their unique practices. These specialized artifacts, although perhaps incompatible or even incongruent, must be synchronized within the same design project. In the case of the commuter station, John did the stop and plot to calibrate various representations to a point in time. Further, this notion of a representational ecology (Bergman et al 2007) takes on a situated character, as designers idiosyncratically assemble unique groups of representations for specific changes. Stephanie's example showed how the representational ecology was derived in a situated fashion, based on anticipated information needs with her collaborators. Both of these examples highlight the situated role of representational ecologies in design that directly question any rigid or highly standardized infrastructure for managing such tasks – instead they call for much higher levels of flexibility and adaptability.

P2: Information systems that afford the synchronization and representational flexibility among heterogeneous sources will more effectively enable the generation of innovations across doubly distributed design networks than those that apply a standard process with standardized representational forms.

Perhaps the most unexpected finding was the need to recreate geometry to understand it, which was found in both the Gallery Project (Michael) and Convention Center Project (Mike). In the Gallery Project, neither Michael nor the steel fabricator revealed all the problems with the design by inspecting the existing design models – although all of the design information was, in fact, available in these models. Only when Michael recreated the design did he discover the problems. Recently, Avital and Te'eni (2008) identify principles relating to *generative* information systems that support the creation of novelty. Rather than seeking novelty, our insights point to a need for re-generativity in systems that support doubly distributed design networks – or the recreation of design data for the purposes of learning and understanding. This insight is consistent with Østerlund's (2004) notion of "re-localization" evident in distributed medical teams. Re-localization refers to the practices of nurses and doctors who redundantly recreate medical histories in order to learn about the patients. Both of these examples point to situations where the integrated, single model / single-point of data capture paradigm may not apply to cases where intimate familiarity with content is essential in a distributed setting.

P3: Information systems that afford the recreation of local design data through regeneritivity of data from heterogeneous sources will more effectively enable the generation of innovations across doubly distributed design networks than those that apply a single, standard, integrated model.

Finally, our study indicates the need for traceability across both space and time. This idea traceability is consistent with the idea of focusing on a context (Boland et al 1994; Majchrzak et al 2005) for systems that support distributed design, however, the conceptualization of context emphasized in these studies involves transparency across information within information systems. While this is certainly critical, it tends to emphasize the capabilities of the system – the agency for transparency lies with the system. However, our data points to the need for designers to interactively navigate historical and cross-sectional contexts – where the agency lies with the designer, often in conjunction with the systems. Although this may appear to be a slight adjustment to the way that context is addressed, we feel that the notion of traceability further implies the agency and interactivity, while still accommodating the contextual transparency evident in studies of distributed design (e.g., Majchrzak et al 2005).

P4a: Information systems that afford temporal traceability will more effectively enable the generation of innovations across doubly distributed design networks than those that capture single explicit decision logic.

P4b: Information systems that afford spatial traceability will more effectively enable the generation of innovations across doubly distributed design networks than those that apply an integrated data policy across the infrastructure.

The major implications of this research are twofold. First, by critically extending the principles of distributed design (across diverse, dispersed knowledge communities) to contexts of doubly distributed design we are incorporating the material aspects of the IT artifacts that are embedded within the knowledge work of different communities (Orlikowski 2006). Different design communities are involved in a design network solely by virtue of their unique and heterogeneous knowledge – Stephanie does her analysis work through RISA, not the CAD tools of the architects - and any information infrastructure that attempts to integrate and standardize these diverse communities runs the risk of not adequately appreciating the heterogeneity of the technological artifacts.

Second, by emphasizing the material and distributed nature of design changes across doubly distributed design networks, we characterize design iterations in a different light. Design iterations are not only about cognitive generate-test cycles among design individuals (Simon 1996), or the representation of the design through an artifact across a boundary (say between users and developers, e.g. Berente & Lyytinen 2005). Rather, iterations cascade across multiple representations, at different levels of granularity, and across multiple artifacts – both within and outside of the collaboration infrastructure. Further, iterations bring about new sets of iterations and the feedback from such deviations is not always immediate, as Kim's and John's examples indicate. This observation suggests that such iteration could explain the micro-level mechanisms that are implicated in project and industry wide "wakes" of innovation (Boland et al 2007).

Conclusion

According to Cross (2007), the burgeoning design discipline accommodates three broad streams of inquiry. The first, which he describes as "design science," involves research into the theoretically motivated creation and testing of artifacts (consistent with March & Smith 1995; Hevner et al 2004). The second stream of inquiry is "design thinking" and involves guiding the reflective practice of acting designers (in the spirit of Donald Schön). The third, which Cross describes as the "science of design" relates to the use of scientific method (in March & Smith's "natural science" tradition) in focusing on design practice as the subject of research (i.e., the Gregor & Jones 2007 "expanded view" of design research). These three streams ideally work together in a form of dialectic across design–related disciplines to remain relevant while at the same time enjoy a high degree of rigor to inform practice.

Our research into design changes across doubly distributed design networks falls within the "science of design" stream of research. In using well-tested scientific tools of cross-case analysis (Eisenhardt 1989; Yin 2003), we generate principles relating to design activities across such networks, and from them derive theoretical propositions. The goal of this research program is to inform future design science research through testable propositions.

This research is unique, as it goes beyond existing research related to the information technologies that support individual cognition, as well as collaboration across syntactic and semantic boundaries to include considerations for the technological artifacts that are embedded in the design practices of diverse specialties. In doing this, our research offers two overarching contributions. The first involves questioning the singular, integrated architecture-view of IT artifacts intended to support design activities, when applied to doubly distributed design networks. The second involves a re-conceptualization of the notion of iteration within doubly distributed design networks. In general research articulates iterations as the discrete generation and testing of specific design alternatives. In a context of doubly distributed design, however, iterations are comprised of cascading changes across a variety of designers and their specialized technologies.

Through these observations and the theoretical principles and related propositions we look to provide the a form of kernel theory (Hevner et al 2004) which can be leveraged for the design of IT that is intended to support doubly distributed design networks such as those in innovative AEC projects. Further, we provide descriptive evidence of a class of design problems for other streams of design-related research. While we identify AEC as a key doubly distributed industry, many of these concepts may apply to other forms of innovative, collaborative activity.

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