HOW ARE TECHNOLOGICAL CHANGES IN BOUNDARY OBJECTS ENACTED IN DESIGN AND CONSTRUCTION NETWORKS?

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ABSTRACT

Interorganizational networks are proliferating as a form of industrial organization. However, the processes by which networks of firms implement boundary-spanning technological changes remain poorly understood. In this paper I explore the implementation of three-dimensional computer-aided modeling tools in 26 design and construction organizations. I analyze empirical data collected over a seven month period to induce a set of antecedent constructs that enable the evolution from 'printed sets of plans' to 'virtual model' boundary objects. The findings highlight the importance of addressing regulative, technological, work, and organizational issues at the interfaces between firms in networks when implementing boundary-spanning technological change.

INTRODUCTION

The ability for organizations to sustain competitive advantage rests in part on the successful implementation of new technologies. Over the past several decades information systems have provided a steady stream of technological changes for organizations to employ to keep apace with competitors. Many of these changes have taken the form of integrated information systems that some researchers contend require a fundamental reexamination of the concepts of markets and hierarchies (Malone, Yates, & Benjamin, 1987). Within hierarchically organized firms, enterprise-wide integrated information system implementation has proven to be wrought with unforeseen hazards (Block, 1983; Davenport, 1998; Sumner, 2000). Block (1983) identified a dozen categories of determinants to explain enterprise-wide information system implementation failure. Despite the potential for failure, the successful implementation of integrated information systems provides a rich source for sustained competitive advantage in firms (Mata, Fuerst, & Barney, 1995; Powell & Dent-Micallef, 1997).

In parallel with the development of integrated information systems, interorganizational networks have increasingly replaced traditional vertically-integrated hierarchies over the past several decades (Barley, Freeman, & Hybels, 1992; Pekar & Allio, 1994). Interorganizational networks were first discovered in the Massachusetts house building industry by Eccles (1981). Eccles described these networks as *quasifirms* where house building contractors maintain long-term contractual relationships with subcontractors even if those subcontractors did not provide the lowest market price to perform their work. He described the *quasifirm* form of organization as existing between the traditional markets and hierarchies outlined in transaction cost economics by Williamson (1975). Williamson (1985) later supplemented his transaction cost framework with the concept of *hybrid* organizations as an intermediate form of organization existing between markets and hierarchies.

Since these early studies of interorganizational networks, research has extended beyond economic exchange arguments to consider networks as a new, independent form of organization (Miles & Snow, 1986; Powell, 1987, 1990). Researchers of the network form of organization seek to understand how interactions between organizations are governed (Granovetter, 1992; Jones, Hesterly, & Borgatti, 1997; Stinchcombe, 1985), how firms select network partners (Beckman, Haunschild, & Phillips, 2004; Galaskiewicz, 1985; Pekar & Allio, 1994), the stability of interactions between networked firms (Gulati, 1995; Powell, White, Koput, & Owen-Smith, 2005), and how knowledge flows across networked firms (Appleyard, 1996; Uzzi & Gillespie, 2002). Although research on interorganizational networks investigates the relational aspects of networks and the knowledge exchanged, interorganizational researchers have largely ignored the interstitial objects that connect the work and provide a vehicle for exchanges of knowledge between disparate organizations in networks.

The rise in research on and usage of interorganizational networks led information systems researchers to investigate the implementation of these systems across organizational boundaries in networks. Numerous researchers found the implementation of interorganizational information systems to be a source of competitive advantage in interorganizational networks (Bakos, 1997; Bakos & Treacy, 1986; Cash & Konsyniski, 1985; Johnston & Vitale, 1988). Cash and Konsynski (1985) proposed that information systems can enable the redrawing of organizational boundaries. Some researchers proposed that interorganizational information systems themselves provide the integrating mechanisms to connect organizations into networks (Argyres, 1999; Johnston & Lawrence, 1988; Venkatrama & Zaheer, 1990).

The linkage between integrated technologies and interorganizational information systems led to a thread of research pursuing the notion that competitive advantage lay in reducing the boundaries of organizations, even to the point of organizations becoming *boundaryless* (Devanna & Tichy, 1990). However, more recent research finds that boundary activities may actually increase in significance in *boundaryless* organizations (Cross, Aimin, & Louis, 2000; Hirschhorn & Gilmore, 1992). Though the formal, hierarchical boundaries may appear to be reducing in importance, integrated information systems can become increasingly important intermediate boundary objects to link the work and enable the exchange of knowledge between disparate organizations in networks (Briers & Chua, 2001; Pawlowski & Robey, 2004).

Star and Griesmer (1989) introduced the concept of *boundary objects* to describe objects that inhabit intersecting social worlds while at the same time satisfying the information requirements for each separate group. Interorganizational information systems are one example of a boundary object that connects the work of different occupational fields (Levina & Vaast, 2005; Pawlowski & Robey, 2004). Other examples of boundary objects include prototypes (Carlile, 2002), sketches (Henderson, 1991, 1999), or designs (Bechky, 2003). These boundary objects play a mediating role to connect the disparate social worlds of the designers and the builders of those designs while at the same time enabling individuals from both groups to conduct their work.

In Henderson's (1999) ethnographic study of the evolution from paper-based to computer-aided drafting among designers we learn that technological change in boundary objects can have a significant impact in the structuring of work and status of individuals within design firms. This study of implementing technological change in boundary objects provides a rich understanding of the difficulties a single firm faces. However, it offers little direction to navigate technological changes in boundary objects that span organizational boundaries. If technological change in boundary objects can erode current patterns of work within a firm, what impact can it have on interdependent firms in interorganizational networks? Though researchers have explored the issues associated with interorganizational information system boundary objects in networks (Briers & Chua, 2001; Pawlowski & Robey, 2004), there is little in the way of guidance on how a network of firms would go about implementing technological changes of this kind. If the successful implementation of interorganizational systems is critical to sustaining competitive advantage (Bakos, 1997; Bakos & Treacy, 1986; Cash & Konsynski, 1985; Johnston & Vitale, 1988), then firms involved in interorganizational networks must understand how to implement technological change in boundary objects to remain competitive.

This paper explores the question of *how firms in interorganizational networks implement technological change in boundary objects*. Extending from previous work on the evolution from paper-based to computer-aided drafting in design firms (Argyres, 1999; Henderson, 1991, 1999; Manske & Wolf, 1989; Robertson & Allen, 1992; Salzman, 1989), I explore the recent evolution from two-dimensional (2D) computer-aided drafting (CAD) to 3D CAD in design and construction networks. The boundary object exchanged between designers and contractors remained stable in the evolution from paper-based drafting to 2D CAD. Designers continued to share designs with the contractor as a set of paper-based line drawings. However, with the evolution from 2D CAD to 3D CAD, the disparate social worlds of design and construction are brought together to co-create a virtual model of the planned structure.

RESEARCH SETTING AND METHODOLOGY

I employed a qualitative approach (Eisenhardt, 1989; Glaser & Strauss, 1967; Strauss & Corbin, 1990; Yin, 1989) to gather and analyze the experiences and perspectives of designers and contractors on their successful implementation of 3D CAD tools. I asked informants to describe two recent projects; one prior to the implementation of the tool, and a similar project after the tool had been implemented where the usage of the tool successful. I then asked the informants to elaborate on the aspects of the implementation that made it successful. I also spent several weeks observing the implementation of 3D CAD within and across design and construction organizations. From this data I developed a grounded understanding of how firms in interorganizational networks successfully implement 3D CAD software and was able to induce a set of antecedent constructs relating to successful boundary object technological change in design and construction networks. Because this boundary object change occurred at the boundary between the intersecting social worlds of construction and design, I analyzed the variances in perspectives in order to explore how implementation issues varied across interorganizational network boundaries.

Sample and Data Collection

Researchers suggest that qualitative case research include employ multiple data collection methods in order to increase the validity of the constructs identified (Eisenhardt, 1989). In this study, I employ multiple data collection methods; including, ethnographic interviews, direct observation, and review of primary documentation. Researchers recommend using multiple case studies to further increase internal construct validity (Eisenhardt, 1991). To accomplish this, I replicated the data collection effort across 26 different organizations in this research investigation. During the course of this research I spent several weeks as an observer of six 3D CAD projects involving both design and construction organizations.

By triangulating the findings across these different cases and data collection methods I strengthen the validity of the findings (Eisenhardt, 1989). The data collection effort took place over a seven month period from June 2004 through December 2004. Of the firms investigated in this project, 13 were construction firms and 13 were design firms. In order to select firms for inclusion in this study, I specifically approached companies that had successfully implemented a 3D CAD tool. Therefore, the organizations in the study were selected for their ability to provide analytic generalization, they were not randomly sampled (Yin, 1989).

Research Context

From 2D CAD to 3D CAD. Argyres (1999) found that the implementation of 3D CAD among the firms that designed and developed the B-2 "Stealth" bomber both enhanced coordination and enabled the creation of an entirely new kind aircraft. He postulated that 3D CAD could be a source for competitive advantage in strategic alliances when compared to earlier advances in CAD. According to one 3D CAD tool provider, this technology will have similar coordination benefits in the design and construction industry. He describes the development of a virtual model of a building with 3D CAD as follows:

> "...a computer model database of building design information, which may also contain information about the building's construction, management, operations, and maintenance. From this central database, different views of the information can be generated automatically, views which correspond to traditional building design documents, like plans, sections, elevations, quantity take-offs, door and window schedules, 3D model views, renderings and animations. Because these resulting documents can be derived from the same database, they are all *coordinated* and *accurate*." (Barron, 2003: 2 emphasis added)

Harty (2005) documented how the adoption of 3D CAD on a large design and construction project led to coordination difficulties between firms. Where this technology creates an opportunity to improve the coordination and accuracy of the design and construction model (Barron, 2003), it can also create coordination difficulties across firms in design and construction networks. Mitropoulos and Tatum (1999) found that the adoption of 3D CAD can be hindered by decision processes within construction organizations. Whyte and her colleagues (1999) determined that 3D CAD software is being adopted more slowly than its predecessor 2D CAD. Harty's (2005) study of the adoption of 3D CAD is instructive in that it suggests that social and organizational contexts need to be taken into consideration to understand the adoption of this technology. He pointed out how the technology had spillover effects beyond the adopting firm (Harty, 2005). However, the process by which design and construction firms in interorganizational networks address these spillover effects and successfully implement boundary object technological change remains poorly understood.

3D CAD is unique when compared to the earlier evolution to 2D CAD technology because it involves designers and contractors working together to co-create a virtual representation of a building. Numerous studies point to the significant changes it introduced within organizations. Manske and Wolf (1989) identified the emergence of new roles to complement new skill requirements within design organizations that implemented 2D CAD. Salzman (1989) also identified how the skill requirements of employees in design firms changed as a result of implementing 2D CAD. Robertson and Allen (1992) and Henderson (1999) each describe how work was restructured within organizations evolving from drafting to 2D CAD. Henderson (1999) further described in her ethnographic account of the implementation of 2D CAD how the relations between employees changed. None of these studies, however, identified changes occurring across organizational boundaries.

With both paper-based drafting and 2D CAD, building information was typically exchanged between firms in the form of a printed set of plans. The plans themselves then became the visual representations upon which discussions within and between design and construction organizations were based. This boundary object (the printed set of plans) between designers and contractors is central for coordination and provides the locus for elaborating and resolving conflicts. The plans span the separate social worlds of designers and contractors and satisfy the information requirements of each, meeting Star and Griesmer's (1989) definition for a boundary object.

Figure 1 illustrates some of the interactions the occupational fields of design and construction have with the 'printed set of plans' boundary object. Architectural designers create conceptual designs either through sketching or the development of computer-aided designs in 2D CAD. This printed set of conceptual design plans becomes the initial boundary object which is shared with engineering designers to analyze and create structural designs which are then reviewed for coordination by trade contractors. The architectural designer incorporates the structural design, refines the original conceptual design, and creates a detailed design which is shared with the general contractor as a printed set of plans. The general contractor reviews this printed set of plans for constructability and provides requests for information to advise the architectural designer of any suggested or required changes. This process of interaction with the printed set of plans goes on throughout the design and construction process until ultimately the general contractors and trade contractors edit (or "redline") the set of plans to reflect what was actually constructed.

Insert Figure 1 about here

Figure 2 illustrates how design and construction occupational fields interact with the 'virtual model' boundary object. With 3D CAD, organizations from the separate social worlds of design and construction are brought together to co-create a 'virtual model' for a building. Design and construction organizations have some flexibility in the extent to which they co-create virtual models. They can focus the creation of the virtual model internal to their own organization, they can co-create the model with other designers or contractors on a building project, or they can move beyond sharing with project partners and co-create the model with material suppliers. In Figure 2, however, we describe the process by which designers and contractors co-create a virtual model boundary object.

Insert Figure 2 about here

Where the evolution of a 'printed set of plans' was separated in time, the co-creation of a 'virtual model' requires overlapping of the work. Some designers described this as "bringing the contractor on board early." It is in these interactive sessions represented in Figure 2 where designers design, analyze, incorporate and refine while contractors review, advise and coordinate. The fact that designers and contractors come from different social worlds with different interpretations of 'printed sets of plans' becomes evident in these sessions. Designers described surprises in this co-creation environment as "we aren't normally thinking about how wall lines interact with the ceiling" while "the guy with building experiences is thinking 'what kind of wall is that?'." This tighter interaction created some problems initially in the co-creation of the virtual model. One contractor described that "there are deep seated issues with getting people from different disciplines to talk to each other and get along."

3D CAD uses virtual objects to represent various elements of a building. When a set of printed plans were shared between organizations, each disparate organization could define the elements as they wished. When a designer or a contractor viewed a set of printed plans illustrating a glass exterior of a building, the contractor might describe it as a curtain wall while an architect might describe it as a facade. However, when individuals from the separate worlds of design and construction are brought together to co-create this same glass exterior, differences in naming conventions can lead to coordination difficulties and conflicts.

Design and Construction Organizations. I investigate the implementation of 3D CAD software in 26 design and construction organizations. Design and construction networks have been the focus of a number of recent innovation studies pointing out issues associated with interdependent, networked nature of this industry and its work (Gann & Salter, 2000; Miozzo & Dewick, 2002; Salter & Gann, 2003; Taylor & Levitt, 2004). Each of these studies identified learning in the project-based design and construction networks as an inhibitor to change. None of these studies, however, investigated technological change in the boundary objects that connect the disparate worlds of design and construction. In this paper I investigate the technological change from the 'printed set of plans' boundary object that connect design and construction organizations to the co-creation of a 'virtual model' in order to better understand how change occurs in these networks.

The design and construction firms included in this study were not selected based on the implementation of a specific 3D CAD tool. I was less interested in the specific tool and more interested in identifying trends across different types of tools that led to successful implementation. I included only firms that had completed at least one project using 3D CAD software. Of the firms included in the study, 13 had completed between one and five 3D CAD projects, 9 had completed between six and twenty-five projects, and 4 had completed more than twenty-six projects.

Table 1 below provides details about the 26 firms included in the study. In addition to data about the specialization of each firm (designer or contractor), I tracked the location of the company headquarters (US, Europe or Asia) and the scale of that firm's operations (local, national or international). Regarding each firm's technology implementation, I tracked the number of 3D CAD projects they had completed (1-5, 6-25, or more than 26 projects).

I also tracked the degree to which the 3D CAD work was co-created with other firms. Four of the firms in the sample were using 3D CAD successfully in their firm without co-creating the 'virtual model' with other firms. Twelve of the firms in the sample co-created the 3D CAD model with another specialist firm on the project (e.g., designers working together with contractors). Ten of the firms in the sample were actually moving beyond co-creating the model between design and construction firms. These firms extended their cooperation in the development of the 'virtual model' of the building with material suppliers (e.g., structural steel fabricators and window manufacturers) who would fabricate elements of the building directly from the model. It was not my original intention or expectation to observe co-creation of 'virtual model' artifacts at this level. However, it instructive to understand the further reaches of the propagation of boundary object technological change.

Insert Table 1 about here

Interview data was collected in interviews of approximately three hours in duration. I collected approximately 90 hours of interview data during the course of the data collection. An interview protocol was used during the interviews to make sure the interview covered the basic discussion points. However, the protocol was designed in such a way to encourage the interviewees to speak at length, in their own words, about their experiences before and during the successful implementation of 3D CAD in the context of specific projects.

In addition to interview discussions, direct observations of six 3D CAD projects involving designers and contractors were made over a period of several weeks. I was invited to attend project and company meetings, to visit project sites, to generally observe the interaction between participants on the projects, and to discuss my observations with my informants within the design and construction organizations involved. I took extensive notes during this process and took digital photographs for use in my data analysis. Interview discussions and noted observations were recorded in a numbered set of field research notebooks. Interview discussions were also recorded using a digital voice recorder.

Whenever possible, I requested hard copies of materials discussed during interview discussions and observations. Data collected included contract documents, process flow diagrams, project schedules, design models, bills of materials, project decision schedules, animations of design models, and any other information that might lend insight into the successful internal and interorganizational implementation of 3D CAD. This primary documentation was attached to my field notebooks and often elucidated concepts that were not entirely clear when reviewing the notes from an interview or observation. Overall, I was able to manage the reliability of the findings by keeping an indexed, organized database of my field notebooks, audio interview files, photographs, and documents collected.

Content Analysis

Because I did not use a structured interview, interviewees were able to spontaneously discuss topics that they felt were important regarding their implementation of 3D CAD software. Interview quotes were only included in the qualitative content analysis if they specifically dealt with the implementation of 3D CAD software. Quotations varied from short quotes to longer, several sentence discussions. The idea was to encapsulate a complete thought that could be compared and contrasted with other quotations to formulate constructs.

I performed a line-by-line microanalysis of the data I collected (Strauss & Corbin, 1990). From the microanalysis process, 282 anecdotal quotes relating to successful 3D CAD implementation emerged from the raw data. All quotations identified in the data that were relevant to implementing 3D CAD were coded into a database. The quotes were roughly equally distributed between designers (n=158 quotations) and contractors (n=124 quotations). These quotes were then analyzed using the constant comparative method (Glaser & Strauss, 1967) to develop and refine a set of 27 conceptual categories. I then systematically analyzed the 282 relevant implementation anecdotes to identify patterns in an axial coding process (Strauss & Corbin, 1990).

IMPLEMENTING BOUNDARY OBJECT TECHNOLOGICAL CHANGE

The content analysis revealed 27 unique conceptual categories that relate to successful 3D CAD software implementation in design and construction networks. Of these antecedents, 14 account for over 85% of the coded occurrences analyzed in the study. In order to emphasize parsimony I will only include the antecedent constructs that represent 85% of the collected data in the following discussion. Researchers suggest that focusing on constructs that represent 80% to 90% of the data to identify key variables (Dunteman, 1989). In Table 2 below, I list the 14 key antecedent constructs of successful boundary object technology implementation. For each determinant I include the frequency of quotations for designers, for contractors, and for all firms in the study.

Insert Table 2 about here

Upon closer examination of the determinants presented in Table 2, I observe that there is both strong agreement and variance in the frequency of responses for each key antecedent when comparing the implementation perspectives across occupational fields. This is not surprising given the separate social worlds from which designers and contractors originate. By comparing relative frequencies across the design and construction functions we can discern more distinctly the separation of the antecedents across design and construction implementation perspectives. The difference between the relative frequencies for designers and contractors for each key antecedent are tabulated in Table 3. For each antecedent the number of standard deviations from the mean of the variances in the frequencies is listed.

Insert Table 3 about here

Designer's perspective of 3D CAD implementation

It is more important for designers than contractors to *address issues of liability* and to *address contractual constraints* (1 to 2 standard deviations from mean variance). When the printed plans were the boundary object connecting designers and contractors, the plans contained a notation that indicated they were not to scale. With the co-creation of a virtual model boundary object, it is no longer feasible to create designs that are not to scale. Contractors must be able to plan production and fabrication from the virtual model and, as such, dimensions and the connections between objects in the building information model must be precise. This introduces new liability considerations for design organizations. With printed plans that are not to scale, contractors make adjustments to accommodate precise connections between building objects. With a virtual model, however, if a dimension is imprecise and an element does not connect to a building properly during construction, then a contractor can claim that this is the fault of the designer. Designers explained that:

> "in design professional's drawings, the dimensions are not exact, a contractor interprets these and creates shop drawings with exact dimensions … if a dimension is wrong it's the contractor's fault, if derived from the 3D CAD model the architect would be responsible"

This comment was echoed by a contractor who described why, in some instances, they recreate the 3D CAD model even when it is furnished by the architect. He described this concern over liability as follows, "if we get a BIM model from an architect there may be mistakes since the architect doesn't guarantee that the model is correct." Surprisingly, issues of liability had not been addressed explicitly in contracts. Designers described 3D CAD technology as being sufficiently new that it had not been contemplated by the legal profession. Firms that successfully implemented 3D CAD within their design and construction network made only minor modifications to the contract documents. Interestingly, in some cases the virtual model co-created by the designers and the contractors became a component of the contract. One designer describes the virtual model becoming part of the contract documents as follows:

> "in our last project the 3D CAD model became part of the contract documents … the legal side of this is not too complex but there is a fundamental distrust of digital data, you have to tell the structural steel fabricator that the data is accurate"

More generally, designers spoke of contract changes required to successfully implement 3D CAD in their network as needing to "add a paragraph or two on a case-by-case basis" or "we only added a front page to the contract." Although the virtual model is co-created across designers and contractors, it takes its initial form in design organizations. One of the stated benefits of 3D CAD over 2D CAD is more accuracy (Barron, 2003). However, achieving that accuracy requires design firms to *address contractual constraints* and *address issues of liability*.

Contractor's perspective of 3D CAD implementation

In contrast to designers, successful implementation of 3D CAD in contractor organizations focused on working with designers to *cross-pollinate ideas across firms* (2 to 3 standard deviations from mean of variance). The idea that design and construction firms would cross-pollinate ideas with 3D CAD would seem to indicate that this level of interaction did not exist in the past. Unlike the exchange of a set of printed plans with paper-based drafting and 2D CAD, the co-creation of a virtual model requires disparate design and construction organizations to work together more closely. In doing so, construction firms are able to more clearly articulate their knowledge of constructability issues and get changes into the model that otherwise would have had to be worked out in the field during construction or later "with a hammer."

According to contractors, the co-creation of a virtual model enabled firms to "swap roles to understand what is important to other specialists" and "by putting teams together with the model we're able to get unintended benefits." One firm described that they were able to gain an extra floor in the building due to cross-pollination of constructability ideas in design:

> "normally this building would be 15 foot floor-to-floor height, we gained a floor in the building by achieving a 14 foot floor-to-floor height"

Contractors also expressed the need to *experiment with technology* more frequently than designers (1 to 2 standard deviations from mean of variance) when implementing 3D CAD. Contractors have been described by researchers as having difficulties adopting new technologies, in particular 3D CAD (Mitropoulos & Tatum, 1999; Whyte, Bouchlaghem, Thorpe, & McCaffer, 1999). In contrast, designers have been described as being creative and engaged in experimenting with new ideas (Henderson, 1999; Salter & Gann, 2003). In order to successfully implement 3D CAD, contractors need to develop a more experimental attitude. One contractor described that "one big hurdle for 3D CAD is inertia we've always done it this way, we're a conservative industry." Another contractor described an initial passive resistance to 3D CAD as "a lot of saying 'yes' but nodding 'no'... not in my back yard." Some contractors described a process of as long as six months of experimentation with 3D CAD, hiring and replacing numerous CAD managers, and conducting a number of team-building exercises before achieving successful implementation.

A practical concern for contractors vis-à-vis designers in implementing 3D CAD was the need to *work with firms using the same software* (1 to 2 standard deviations from mean variance). When a designer implements 3D CAD, their firm can build a virtual model with their own internal resources or co-create the virtual model with the contractor. However, for a contractor to implement 3D CAD successfully it requires the initial building information model input from the designer. Otherwise, the contractor has to recreate the entire design. In the words of one contractor "even if I can use 3D CAD, if the designer can't use it why bother." Another contractor describes their experience on a recent project where their partners did not use 3D CAD as follows:

> "on our last project all our partners were still using 2D CAD so we had to constantly go from 3D to 2D to communicate files rather than slicing and dicing into layers"

In contrast with designers, in order for contractors to successfully implement 3D CAD they must take advantage of opportunities to *cross-pollinate ideas across firms* about constructability, they must deal with inertia against change in their occupational field to *experiment with technology*, and finally they must identify and *work with firms using the same 3D CAD software*. Construction firms that address these three areas are able to successfully implement technological change in the boundary object that connects their work to design organizations. In doing so, construction firms identified tremendous increases in productivity. One firm described how on their first implementation of 3D CAD they were able to reduce the number of revisions from a running average of 30-35% to 10%. And the accuracy continued to improve with the move from using a set of printed plans developed by a designer to co-creating a virtual model with the designer.

Shared perspectives on 3D CAD implementation

In addition to the specific perspectives of designers and contractors, there were a set of shared perspectives common across both occupational fields. The antecedent constructs of similar importance (from 0 to 1 standard deviations from mean variance in Table 3) to designers and contractors can be classified into four areas; at the organization interface, at the technology interface, at the work interface, and internal change management. I will discuss the findings in each of these areas in the following sections.

Organization interface. Designers and contractors both reported that addressing interfaces between their respective organizations was critical to successfully implementing 3D CAD tools. This area contains the largest relative frequency of responses. At the organizational interface between designers and contractors, networks that *increase collaboration between firms* are more effective at implementing 3D CAD across organizations. One contractor describes this collaboration as a way to both eliminate conflicts and to identify opportunities for improving the design. The contractor described how with improved collaboration the designer "gets input from different people" and in doing so "immediately sees interferences especially across disciplines like a pipe going through a beam." A contractor also described how improved collaboration with the designer actually created opportunities to increase the density of a building. The contractor indicated that "in a few cases (the designer) identified spaces where we can route ducts that would normally be for another system." Attaining the benefits of *cross-pollinating ideas across firms* described earlier is contingent upon *increasing collaboration between firms* in the design and construction network.

Some firms in the sample who successfully implemented 3D CAD tools progressed beyond collaboration to *develop partnerships between firms* in the network. An architect described how "when you have ongoing relationships you can leverage learning to work together with (3D CAD) over and over again." The architect described this learning that comes through partnerships as "a function of percolation." A contractor also described the use of partnerships in successful 3D software implementation across designers and contractors in terms of learning. The contractor described that "establishing more partnerships and not working with different firms from project to project is important as it takes time to learn to work together with a new technology and develop a common strategy." Design and construction firms that address interactions through collaboration and partnership are able to strengthen interorganizational learning associated with the new technology.

A smaller group of firms in the study advanced beyond collaboration and partnership and explored how 3D CAD could be implemented to improve processes beyond their own firm. In doing so, these firms *understood shared interests among firms* in their network. With the limited meaningful interaction available using a printed set of plans, design and construction firms had difficulty understanding each others' interests. If a designer does not consider a contractor's interests and vice-versa, the implementation of 3D CAD or other technologies in the design or construction organization can be counterproductive to the other due to interdependencies in the work. One contractor interviewed described how a sharing of interests is a step beyond partnership. They described that:

> “twice per year we have a meeting to discuss how we can make our partnerships deeper and more profitable for both partners … partnership is not just an empty phrase, we want each other to succeed.”

An architect in the study made a similar claim, in this case stressing how improving the interactions between designers and contractors is more important than issues related to technology implementation. The architect pointed out that:

> "developing cooperative relationships is more important than the technology … participants need to sit around the same table and realize their shared interests.”

Although there were different degrees to which firms in the sample addressed organizational interfaces between designers and contractors, firms that successfully implemented 3D CAD improved collaboration, developed partnerships, or moved beyond partnership to understanding each other's shared interests. This highlights the fact that 3D CAD software impacts both designers and contractors, even if they adopt the technology separately.

Technology interface. In addition to addressing organizational interfaces, both design and construction firms must *address the interoperability of technology* at the technological interface between their firms. In other words, in order to co-create a virtual model, the 3D CAD software in both firms must be capable of opening and editing the electronic building information model.

One contractor described a recent project where all the participating firms were using 3D CAD but that "there were interoperability problems (due to) 20 different file formats." Generally, firms addressed the technology interface between organizations by requiring their partners to use the same 3D CAD software of the same version. One designer describes how they successfully implement 3D CAD across their design and construction network as follows:

> "all our (partners) have to be on IFC compliant software of the same version … it's in the contract" [Note: 'IFC' refers to Industry Foundation Classes, a content standard for 3D CAD objects in the building industry]

Achieving the potential of 3D CAD requires firms to share and co-produce electronic files of buildings. To do so, interfaces between firms and technologies need to be addressed to accommodate the development and learning of interorganizational routines. The deeper the relationship that bridges the interactions between designers and contractors, the more likely firms are to develop novel solutions to design and construction problems that benefit both partner firms.

Work interface. I spoke of the development and learning of interorganizational routines and how addressing the interfaces between organizations and technologies in networks can help to address these. In this section I will describe more specifically how the scope and pattern of work across firms changed for design and construction firms that successfully implemented 3D CAD software. As one architect described, "the big change with (3D CAD) is not technological, it's changing the process." Design and construction firms that successfully implemented 3D CAD *redistributed work among firms, developed standards for interaction,* and *developed a system understanding of the project.*

The key antecedent of *redistributing work among firms* in design and construction networks was the most cited construct in the study (responses relating to this construct alone account for 13.5% of all responses). Both designers and contractors described how the use of 3D CAD software shifted some of the work traditionally done by contractors and material suppliers into the domain of the designer. With the development of a virtual model, designers must provide more detailed and more accurate models. Contractors must also change their work practices to successfully accommodate 3D CAD into their work. One contractor described how "in order for (3D CAD) to work, the flow of work had to change … we're relying more and more on 3D stations in the field." The pattern of work is changing as a result of technological change in the boundary object connecting the work of designers and contractors. Work that used to be completed separately in company offices is now being shifted into the field where designers and contractors can co-create virtual models together more effectively.

A contractor describes the shift in work from a supplier to a designer stating that:

> "the specification process for one complex building material took 100 to 150 parameters and 100 phone calls to define, we resolved this by moving the knowledge to the step where the architect specifies that product."

In response to the changing scope and pattern of work introduced by 3D CAD, a designer that successfully implemented the boundary object technological change described that they:

> "bring sub trades forward so that the steel (contractor) works with the engineer and the window manufacturer works with the architect… it yields better technical detailing"

In the move from 2D CAD to 3D CAD, work is being redistributed among firms in the network. However these redistributions are not enacted without difficulty. With 3D CAD, some work is redistributed from contractors to designers. However, for the network to accrue the benefits of this additional work, the virtual model must be used by firms downstream in the process. One example of a designer's and a contractor's breakdown in process was described as follows:

> "if everyone doesn’t follow the process it all falls apart … if the (contractor) ignores the upstream designers' (3D CAD model) in one fell swoop the process is stopped and the benefits disappear"

Examples such as this illustrate the mutual adjustment required by firms in the network in order for implementation of 3D CAD to be a success at the level of the network. If one of the partners fails to adjust and utilize the extra work performed by the designer then 3D CAD implementation fails. Design and construction firms that were able to manage the mutual adjustment process and successfully implement 3D CAD developed tighter collaborations and partnerships. Improving the relationships at the organizational interface in the network enabled design and construction firms the flexibility to redistribute work.

Another key antecedent that relates to the changing patterns of work required by 3D CAD software is the *development of standards for interaction* between firms. After work has been redistributed and firms mutually adjust, design and construction firms must begin accessing and developing a single virtual building information model. One designer described how they addressed the development of interaction standards as follows:

> “we set up coordination between disciplines so that the architect never touches the structural pieces, the structural engineer never touches the architectural pieces and if there is a change, there must be a web meeting … we require on all projects a basic set of rules be followed.”

Alongside the *redistribution of work* and *developing standards for interaction*, both design and construction firms expressed the need to *develop a system understanding* of the design and construction process. In other words, just as shared interests enabled design and construction firms to understand and consider each others' needs, the change in scope and pattern of work required design and construction firms to understand each others' work. Design firms described hiring designers with actual construction experience who understood "how things go together." Construction firms reported similar changes in hiring employees with more design experience.

Internal change management. All of the changes discussed thus far relate in some way to how design and construction organizations, work patterns, and technologies interact with each other. Since the technological change was in a boundary object that connects designers and contractors this is to be expected. However, firms also reported addressing issues of change management within their organizations. In design and construction organizations, firms were only able to successfully implement 3D CAD after they were able to *obtain sufficient training*. Another key antecedent for explaining successful 3D CAD implementation was when firms *worked with an external change agent*. Firms described a "Boeing effect" where larger design and construction firms would require the smaller partners in their network to implement 3D CAD. Other firms described certain projects being of significant importance driving firms to implement 3D CAD. In the case of design and construction firms based in Europe, several described working with national agencies that cover the initial costs of learning 3D CAD.

DISCUSSION

This research demonstrates how technological change in boundary objects in interorganizational networks can require considerable mutual adjustment in the interfaces between interdependent organizations. Previous research has shown how changes to boundary objects within organizations have restructured work (Henderson, 1991, 1999; Robertson & Allen, 1992), changed relationships between employees (Henderson, 1999), and changed the skill requirements for the various roles (Manske & Wolf, 1989; Salzman, 1989) in design firms. Other research on the successful implementation of 3D CAD as an interorganizational information system in the defense aviation industry found agreement on a technology platform and object naming conventions was central to implementation success (Argyres, 1999). I observe each of these phenomena occurring in boundary object technological change across organizations in an interorganizational network.

Each of the investigations into the implementation of 2D CAD to replace paper-based drafting discovered that boundary object change restructures work and, in doing so, changes the skill requirements for employees in design firms (Henderson 1991, 1999; Manske & Wolf, 1989; Robertson & Allen, 1992; Salzman, 1989). I identified this in the interdependent work interface that connects designers and contractors. The introduction of 3D CAD across design and construction organizations required work to be restructured, requiring design and construction firms to *redistribute work among firms*. This change also shifted skill requirements across design and construction firms. Firms described needing to *develop a system understanding* of each others' work. This caused both design and construction firms to change their hiring practices and also led to the emergence of new roles within both firms.

In addition to the *redistribution of work* among firms and the *development of a system understanding* of work, in interorganizational boundary object change I identified the need to *develop standards for interaction*. Though, not a study of boundary object change, Argyres' (1999) investigation of the implementation of 3D CAD in the defense aviation industry also identified the standardization of work practices as a key component to 3D CAD implementation success. He described a 'deep standardization' which enabled teams from different organizations to work together more seamlessly, decreasing the amount of coordination required to do the work. Within a firm, employees who work together on a continual basis can work together more seamlessly to adjust to changes in work. However, in a network of firms, collaboration on one project does not necessarily mean there will be collaboration on other projects.

In the development of the B-2 bomber (Argyres, 1999), the firms in the project network will not necessarily work together on the next aircraft development project. In the design and construction industry projects are smaller in scope and shorter in duration than an aircraft development project. The composition of design and construction firms in a network can be stable, but fluctuations in participation and lapses in time between projects make learning how to work together with the new boundary object a slow process. *Developing standards for interaction* is an important antecedent to address in interorganizational network boundary object change.

Henderson (1999) described how relationships between employees in design organizations changed as a result of the implementation of 2D CAD. My investigation of interorganizational boundary object change also revealed a significant organizational interface component. Change in the boundary object created changes in the work across design and construction firms. To address the changing scope and patterns of work firms in interorganizational networks *increased collaboration*, *developed partnerships*, *understood each others' shared interests*, and ultimately were able to *cross-pollinate ideas across firms*. In Henderson's (1999) investigation the evolution from sketches to 2D CAD disrupted relationships and the CAD implementation was described as a failure. I focused my data collection on design and construction firms that had successfully implemented 3D CAD. These firms addressed relational disruptions caused by change in the boundary object by strengthening the relationship between organizations when implementing 3D CAD. Argyres (1999) also identified the importance of a trusting relationship between organizations implementing 3D CAD.

In addition to the organization and work interface concepts identified by previous researchers of boundary object change within firms, I identified regulative interface and technology interface issues in networks. Firms in design and construction networks make technology purchase decisions independently. Where a single organization may standardize on a specific software platform, in interorganizational networks this is not necessarily the case. Argyres (1999) found that the three principal firms in the B-2 bomber development alliance were each using different 3D CAD platforms. They agreed to standardize on a single 3D CAD platform for the B-2 project. Argyres also identified the development of a 'technical grammar' which enhanced the interoperability of the file exchanges. Like the defense aviation network study by Argyres (1999), firms that successfully implemented boundary object technological change in design and construction networks *addressed interoperability of technologies* and *worked with other firms using the same 3D CAD software*. The issue of interoperability has been described as a critical problem in the fragmented design and construction industry. A report by the National Institute of Standards and Technology in the United States described inadequate interoperability of technology in the design and construction industry in the United States alone as a $15.8 billion problem annually (Gallaher, O'Connor, Dettbarn, & Gilday, 2004). When boundary object change extends beyond the organizations boundaries into a network, issues of technology interfaces must be addressed for successful implementation to be achieved.

In interorganizational networks, firms enter into collaborative agreements, typically in the form of contracts. However, when boundary object technological change occurs across organizations, the changes in the work interface must be regulated in some way. To a large extent, strengthening organizational interfaces was critical to managing the change in risk profiles associated with the boundary object change. However, certain regulative formalities needed to be introduced at the interface between designers and contractors. Networks that successfully implemented 3D CAD addressed redistribution of work by *addressing liability* and *addressing contractual constraints*. In my study this was particularly important for designers whose scope of work was being increased by the redistribution. Within an organization, issues arising from the redistribution of work would be managed within the hierarchy. However, in interorganizational networks where firms work together in the absence of an orchestrating firm, redistributions of work caused by boundary object technological change can shift liabilities and require new contractual arrangements.

The antecedent constructs at the interface between design and construction organizations relating to the implementation of 3D CAD are illustrated in Figure 3. The work interface and the organizational interface antecedent groupings replicate for interorganizational networks the general findings of Henderson (1991, 1999), Manske and Wolf (1989), Robertson and Allen (1992), and Salzman (1989) from studies of boundary object change within organizations. Within a firm, the organization and work interface is between individuals or teams that work together on a more or less continual basis. However, in project-based interorganizational networks, the interface between a pair of specialist organizations on one project may not continue across future projects. The mutual adjustment required to address organization and work interface issues across organizations can therefore be more arduous than across individuals or teams within an organization. The technical interface and regulative interface antecedents were not previously identified in studies of boundary object change within organizations..

Insert Figure 3 about here

In addition to the interface antecedent groupings, design and construction firms needed to address internal change management issues associated with the technological change to 3D CAD. Both design and construction firms needed to *obtain training* in 3D CAD before they could successfully implement the technology. Both design and construction firms also described the value of *working with an external change agent* to successfully implement 3D CAD. Though this is not identified in previous studies of boundary object change, interorganizational network researchers have described how external agencies such as the National Institutes of Health in biotechnology networks facilitate change (Powell et al., 2005).

This paper introduces a set of antecedent constructs that interorganizational networks must consider when introducing technological change in the boundary objects that connect their work. Extending knowledge of boundary object change from the organizational to the interorganizational level has significant implications for understanding the process by which innovations are implemented in the rapidly proliferating interorganizational networks. Firms populating these interorganizational networks can increase their competitive advantage through the successful implementation of boundary-spanning technologies. However, firms in interorganizational networks and developers of innovations for firms in interorganizational networks must understand that boundary object changes impact collective ways of knowing both within and across organizations. This research shows that the impact of known organizational and work interface issues are magnified when extended to interorganizational networks. It also introduces a set of technology and regulative interface concepts that apply to boundary object change in networks. In doing so, this research contributes to a more complete understanding of boundary object technological change.

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TABLE 1

Details of design and construction organizations investigated

Firm	Occupational Field	Location of head-quarters	Scale of operations	Number of 3D CAD projects completed	Extent to which 3D CAD virtual models were co-created
1	Contractor	US	International	6-25	Into Supply Chain
2	Contractor	Europe	International	6-25	Across Project
3	Contractor	US	National	1-5	Across Project
4	Contractor	Asia	International	1-5	Within Firm
5	Contractor	US	International	>26	Into Supply Chain
6	Contractor	US	National	6-25	Across Project
7	Contractor	Europe	International	>26	Into Supply Chain
8	Contractor	Europe	National	6-25	Across Project
9	Contractor	Europe	International	6-25	Into Supply Chain
10	Contractor	Europe	International	>26	Into Supply Chain
11	Contractor	US	Local	1-5	Into Supply Chain
12	Contractor	US	Local	1-5	Across Project
13	Contractor	US	Local	1-5	Across Project
14	Designer	US	National	6-25	Into Supply Chain
15	Designer	Europe	National	6-25	Into Supply Chain
16	Designer	US	Local	1-5	Across Project
17	Designer	US	National	1-5	Within Firm
18	Designer	US	National	1-5	Across Project
19	Designer	US	International	6-25	Within Firm
20	Designer	Europe	International	1-5	Within Firm
21	Designer	US	International	1-5	Across Project
22	Designer	US	International	>26	Into Supply Chain
23	Designer	US	International	1-5	Across Project
24	Designer	Europe	International	1-5	Across Project
25	Designer	US	International	1-5	Across Project
26	Designer	Asia	International	6-25	Into Supply Chain

TABLE 2

Antecedents of successful 3D CAD implementation cross-classified by occupational field

	Occupational Field		
Antecedent	Relative frequency of designer responses (n=158)	Relative frequency of contractor responses (n=124)	Relative frequency of all firm responses (n=282)
Redistribute work among firms	14.6	12.1	13.5
Increase collaboration between firms	9.5	8.1	8.9
Develop partnerships between firms	7.6	7.3	7.5
Develop standards for interaction	6.3	8.1	7.1
Experiment with technology	5.1	8.1	6.4
Understand shared interests among firms	6.3	6.5	6.4
Develop system understanding of project	5.7	5.7	5.7
Address interoperability of technology	6.3	4.0	5.3
Work with firms using same software	3.8	6.5	5.0
Obtain sufficient training	4.4	4.8	4.6
Address issues of liability	6.3	1.6	4.3
Address contractual constraints	5.7	1.6	3.9
Work with an external change agent	4.4	2.4	3.6
Cross-pollinate ideas across firms	0.6	6.5	3.2
Miscellaneous remaining antecedents which when combined account for less than 15% of responses for all firms	13.3	16.9	14.9
Column Totals	100	100	100

TABLE 3

Cross-comparison of relative frequencies for key antecedents across occupational fields

Key antecedents	Relative frequency for designers minus relative frequency for contractors (in percent)	# of standard deviations from mean of variances
Address issues of liability	+4.7	1 to 2
Address contractual constraints	+4.1	
Redistribute work among firms	+2.5	0 to 1
Address interoperability of technology	+2.3	
Work with an external change agent	+2.0	
Increase collaboration between firms	+1.4	
Develop partnerships between firms	+0.3	
Develop system understanding of project	+0.1	
Understand shared interests among firms	-0.1	
Obtain sufficient training	-0.4	
Develop standards for interaction	-1.7	
Work with firms using same software	-2.7	1 to 2
Experiment with technology	-3.0	
Cross-pollinate ideas across firms	-5.8	2 to 3
Mean of variances	+0.3	
Standard deviation	2.9	

FIGURE 1

Paper-based 'set of plans' boundary object evolution enacted through interactions across occupational fields

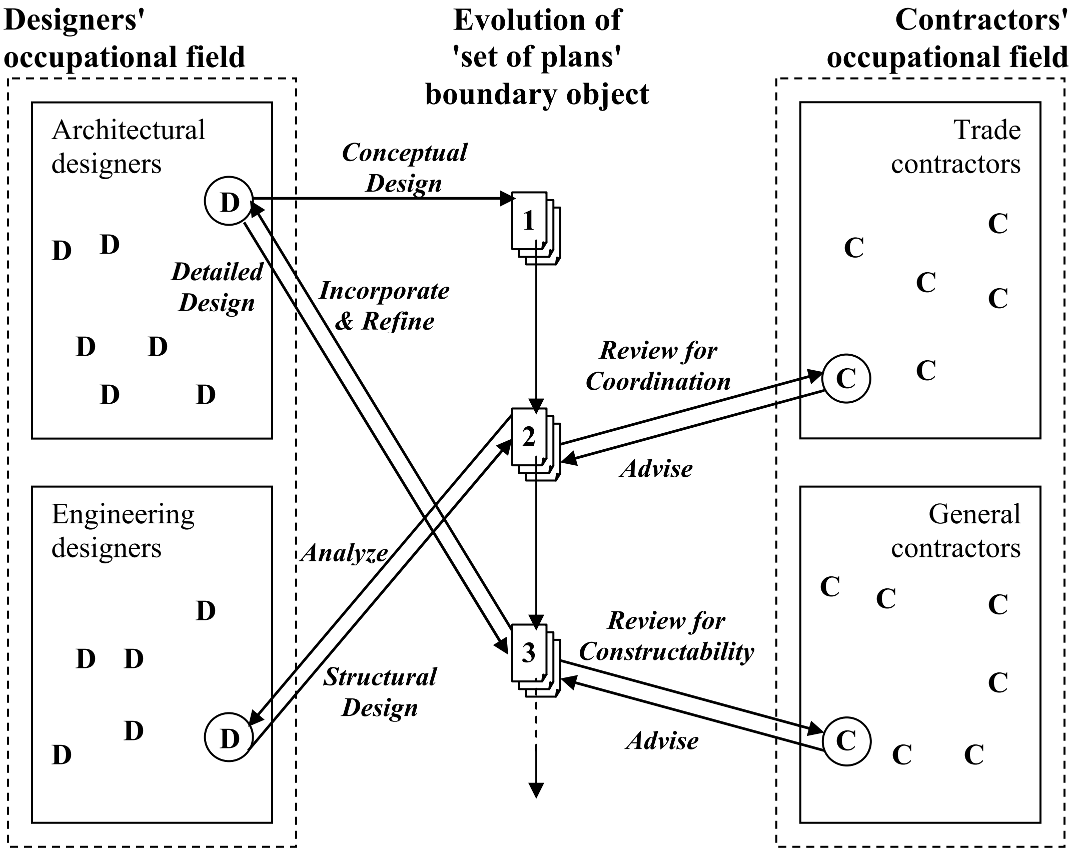

FIGURE 2

'Virtual model' boundary object evolution enacted through interactions across occupational fields

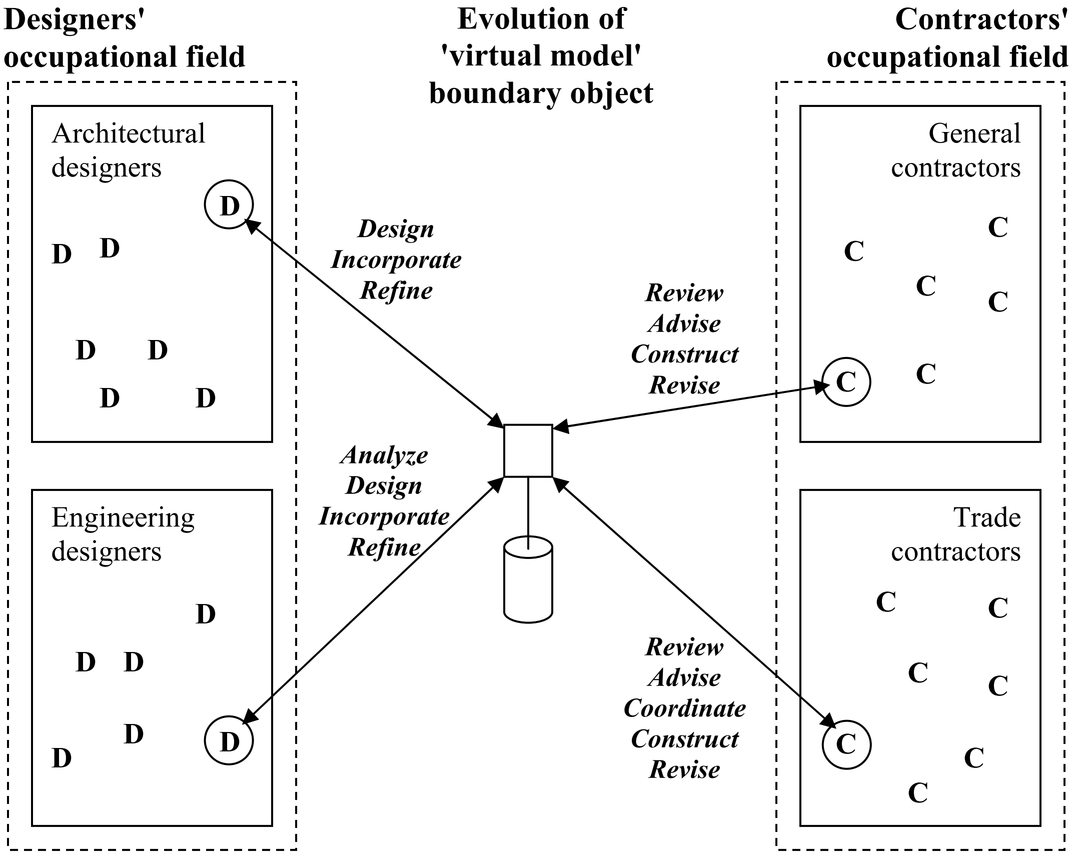

FIGURE 3

Antecedent framework for implementing boundary object technological change across occupational fields in interorganizational networks