7-11-2008

Path Creation with Digital 3D Representations: Networks of Innovation in Architectural Design and Construction

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茅|Sprouts Working Papers on Information Systems ISSN 1535-6078

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Abstract
We examine the wake of innovations in architecture and construction propelled by the adoption of digital three dimensional (3D) representations of buildings and their parts. Departing from the traditional view of innovation that treats information technology adoption as an unproblematic, singular event, we examine IT induced innovations and their consequences as path creation created by the network of professional communities involved in architect Frank Gehry's projects. We report the results of a retrospective case study of 3D representation enabled and triggered innovation during the design and construction of the Peter B. Lewis Building at Case Western Reserve University. Our analysis suggests that the consequences of a complex information technology innovation like the use of digital 3D representations of buildings and their part cannot be fully understood as a singular adoption event. Instead, a more holistic and integrated view of the innovation process as continuous path creation by multiple actors sharing practices and feedback across professional communities while they appropriate 3D representations is required. Information technology innovation is not a single event created by a heroic individual or champion, but it involves multiple agents' mindful deviations from established paths of practices and resource use. We observe that the use of 3D representations breaks down the traditional loosely coupled system in construction that relied on 2D representations to share information between different contractors. These representations essentially black-boxed and hid most information how to build the building or how different parts of design interrelate with one another. To effectively adopt and appropriate the potential of 3D representations requires that traditionally isolated actors during design and construction need to be brought together in a tightly coupled system. This system is arranged around rich and complex boundary objects enabled by the digital 3D representations and their transformations.

Keywords: Diffusion of innovation, 3D digital representation, Path Creation, Path dependence

Permanent URL: http://sprouts.aisnet.org/3-9

Reference: Boland, R.J., Lyytinen, K., Yoo, Y. (2003). "Path Creation with Digital 3D Representations: Networks of Innovation in Architectural Design and Construction," Case Western Reserve University, USA . *Sprouts: Working Papers on Information Systems*, 3(9).

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Introduction

Increased computing power enables new digital representations and practices in a broad array of professions. This is especially true for many information intensive professions such as medicine, chemistry, biology, engineering and architecture that rely on or produce visualizations as knowledge work products, or boundary spanning vehicles (Card, et al, 1999; Friedhoff & Peercy, 2000). Transformations in such professions, however, do not happen automatically. They require a deviation from the traditional ways of using representations in a professional community, and an ongoing assemblage of new digital tools, knowledge assets, work practices, organizational forms and institutional standards.

Since the earliest days of computing in organizations, scholars and practitioners alike have predicted dramatic transformations in work practices, organizational structures, and productivity (Hammer 1990; Huber 1990; Leavitt and Whisler 1958; Malone et al. 1987). Yet, despite those speculations evidence of such dramatic transformations is meager. They are exceptions rather than standard (Robey and Boudreau 1999). Drawing from literature on the diffusion of innovation, information technology implementation, information technology design, and knowledge work, we examine how dramatic the transformational potential and consequences of using digital three-dimensional (3D) representation can be in architecture and construction industries while designing and erecting a building. We assume a process perspective and study digital innovations and its consequences through the lens of path creation by the network of actors involved in the design and construction of buildings. In particular, we analyze the creation of such path creation networks during architect Frank Gehry's projects. The Peter B. Lewis Building at Cleveland is the focus of this paper, although our analysis necessarily links backwards to earlier projects and forwards to future projects as we interview participants and collect documentary evidence.

We employ an actor-network approach (Akrich 1992; Akrich and Latour 1992; Latour 1987) to trace the path creation processes by which Gehry Partners' innovations with digital 3D representations affect their technologies, knowledge, work practices and organizational forms and their construction contractors. Path creation refers to the way an agent mindfully deviates from traditionally reinforced paths of practices and resource use in order to produce a new path of self reinforcing relationships (Garud and Karnoe 2001). In this research, we do not focus on a particular information technology and the "inscriptions" around which its network is stabilized (Latour 1995). Instead, we are interested in understanding the ongoing process of path creation that results in a very different ensemble and configuration of the actor-network. The continued expansion and configuration of the actor-network is caused by spiraling innovations in technology, organization, knowledge and work that cascade from firm to firm during the construction process as a result of adopting 3D digital representations in the architectural design by Frank Gehry. Accordingly, we argue that a complex IT innovation needs to be understood as a cascading wave of path creating actions in the everyday work of actors in multiple communities of practice.

The research contributions of this paper are a fragment of a new theory and empirics on how information technology innovation takes place in networked communities of practice (in our case the architectural design and construction industry) as a result of pervasive digitalization. We examine the path creation processes by which these representations become embedded into innovation lattices and complex actor networks that integrate new knowledge, work practices, technology innovations (tools) and organizational forms.

The remainder of the paper is as follows. We begin by focusing on the role and history of three dimensional representations in architecture and in Gehry Partners' architectural designs. Third section lays out the theoretical framework of the paper and relates it to several related streams of literature. We then follow several complex interactions among multiple actors such as designers, structural engineers, contractors, steel fabricators, glazers, plasterers as they unfolded as the result of adopting 3D representations during the construction of Peter B. Lewis building. The paper concludes by observing implications for further theory building and continued empirical innovations among a network of innovators.

Use of Three-Dimensional Representations in Architecture

A review of the current trade and academic literature demonstrates the significant developments in the potential and utilization of three-dimensional representation technologies such as CATIA software (see http://www.3ds.com/en/brands/catia_ipf.asp, http://www3.ibm.com/solutions/plm/pub1/) in the architectural practices. These systems enable digital design and simulation of the physical products and processes. These systems allow users to tailor their product development capability according to their own particular needs. They can simulate the entire range of industrial design processes from the initial concept to product design, analysis, assembly and maintenance. They can meet a broad spectrum of tasks such as mechanical design, shape design, styling, product synthesis, equipment and systems engineering, NC manufacturing, analysis and simulation, and industrial plant design using an open and component-based architecture.

The lowered cost and improved quality of digital imaging has facilitated the creation of digital representations of buildings that are living, interactive and intelligent (Shih, 1996). These capabilities extend to all elements of the design process and enable different tasks and representations of the building to be dynamically highly interconnected (Lacourse, 2001). Digital representations influenced first architecture in drafting, then in visualization of the end results, and now in more so during the construction. The 3D digital models of the building allow designs information to become at the same time construction information (Saggio, 1997) where the 3D model represents more faithfully “as is” the final building. Over time, these digital artifacts of buildings can be applied, modified and later reused through emerging 3D information management capabilities such as Knowledgeware©,(CATIA) which have been designed to store and find 3D objects for later use (Toupin, 2001). Use of such tools and processes is expected to impact profoundly the garnering of experience and design and construction knowledge, and speed up the evolution of new designs.

For the architect, 3D digital models provide greater latitude and precision because they are built using mathematical equations of descriptive geometry. This allows to locate exactly any point on any surface of the building within any scale. It also allows unbounded experimentation with designs and different surfaces as well as provides tools to verify and modify designs in terms of cost or structural constraints in order to finalize the design (Lindsey, 2001). The models allow high levels of integrity at nearly any scale: when all representations of components that make the building (and associated surfaces) are integrated, even a minute change in one sector or component can be used to propagate all necessary changes to adjacent sectors of the building plans (Greco, 2001).

In consequence, the new 3D technologies enable unforeseen dynamic interaction between representation and analysis tools and multiple designers, and also between designers and the fabricators and the constructors that share these representations. Thereby the impact of accurate representations is experienced in nearly all corners of the building process. These digital tools also change the practice of design as they eliminate earlier design constraints by providing powerful visualization capabilities and affecting the cost/ effort/ error rate of obtaining specific design information (Koutamanis, 2000). This has resulted in increased degrees of freedom to design and build cost-effectively complex structures that were previously impossible to do. As architects have started to develop new approaches to design digitally they have expanded also the appropriation of these technologies in their architectural practices thereby expanding further their design horizons (Prins, 2002). Hence, 3D technology development cycle acts currently as a key driver in changing the language and practice of architecture thereby opening new paths in the construction industries.

The use of 3D information to manufacture directly building components through mass customization is one of the most promising areas of innovation in this industry. This change casts designers into a non-traditional role as they can in future manage centrally the information flows between the production, standardization and prefabrication of components. These practices are also changing contractors' roles into management of assembly (Lindsey, 2001). The extended need for tight integration with manufacturing has driven traditional manufacturing design and imaging to exploit new computer integrated manufacturing (CIM) capabilities that are integrated with the 3D design realm. As a result, software like CATIA have been augmented with manufacturing capabilities. They currently offers modules capable of leveraging a host of manufacturing functions including numerical control, computer aided manufacturing, and prismatic machining (Christman, 2001).

In the construction process applications of three-dimensional representations drive innovation. The lack of standardized forms, shapes and components in 3D designs have spawned a new breed of contractors, who are open to constant change, able to adopt to new construction techniques (Koutamanis, 2000), and who encounter unforeseen situations that require improvisation and creativity, forcing them to deviate from standard procedures. The complex geometries enabled by 3D technologies spawn currently multiple new construction techniques including CNC-guided plasma cutters to cut structural steel members, computer-controlled machinery to bend and weld flanges, and global positioning systems to guide in the placement of walls, roofs and beams (Gragg, 1999).

Use of 3D representations in Gehry's work

The work of architect Frank Gehry and his firm, Gehry Partners, forms currently a striking example of how 3D digital representations have transformed the professional practice of architecture. Gehry Partners act currently at the forefront of using three-dimensional modeling in architectural designs in order to achieve extremely complex surface geometries that are typical to Gehry's architectural language. These forms cannot be conveyed easily in traditional two-dimensional representations. The software (CATIA) which they adapted as one of the first architectural firms in the world from the aerospace industry has resulted in a cascade of innovations in their construction projects by enabling designs which all the time push the boundaries of accepted practice in almost all aspects of building design and construction. In this paper, we report the results of a retrospective case study of a completed project by Gehry Partners, the Peter B. Lewis Building at Case Western Reserve University, which currently is one of the most complex architectural designs in the world (see figure 1).

Figure 1. The Peter B. Lewis Building

Gehry Partners first used the CATIA system serendipitously in a project with extremely tight time and budget to build a large "Fish Sculpture" for the Barcelona Olympics in 1992. That project was a striking success and increased their confidence in the use of 3D technology. The experience has been expanded over time and the use of 3D technologies has enabled them to propose and successfully build ever more daring building forms, including the highly praised Guggenheim Museum in Bilbao, Spain, the Experience Music Project in Seattle, the Disney Concert Hall in Los Angeles, the Bard College Performing Arts Center and the Lewis Building. Examples of actual three-dimensional representations from the Guggenheim Museum are shown in Figure 2. These have resulted in more intense and complex exploitation of 3D representations in most aspects of building design and with each new project, the surface geometries have became more complex, and the requirements for innovation in construction techniques became more pronounced.

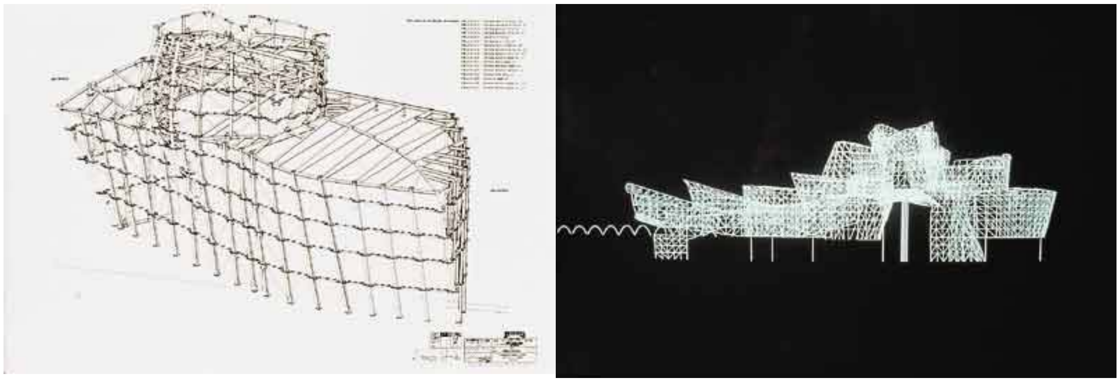

Figure 2. Examples of 3-dimensional representations- structural models of Guggenheim museum

Gehry Partners forms thus uniquely suitable site for studying the use of 3D representations in architecture and construction because they have made digital technology a source of continued innovation and a means to reorganize their whole design and construction activity. Their unique way of incorporating 3D representations with novel architectural ideas in the design, engineering and construction of their projects distinguishes their design practice from most architectural firms. As a result, Gehry Partners is continually designing structures, which push the limits of, or actually break from, existing paths in the construction industry in terms of shape and form. Their innovations in design and construction have also stimulated new forms of “mass-customization” where individual pieces of a building, such as its windows or wall framing, are mass-customized, using digital representations to guide their manufacturing process.

Theoretical Framework

Past Related Research

We explore how new and complex digital technologies and tools enable path-creating innovations in multiple dimensions over a sustained period of time in a specific field of practice. Our study crosses four separate and influential streams of research: diffusion models of information technology adoption; impact models of technology use; design theories of building effective digital tools; and the use of multiple representations and artifacts in highly professional knowledge work.

Research on the *diffusion of information technology* presumes primarily that innovation diffusion is a sequential process unfolding over specific stages in order over time (Attewell 1992; Cool 1997; Cooper and Zmud 1990; Fichman and Kemerer 1997; Rogers 1983; Swanson 1994; Zmud 1984). The focus of these studies is to primarily identify factors that affect the pattern of diffusion in time and space. Although these studies have provided rich insights into the general shape of growth in, the adoption of and expenditures on digital technologies, they give us little insight into how their increased use results in social, economic, technological, and institutional transformations. Furthermore, these studies often assume that the innovating social systems have no history and no feedback and they focus on singular events or adopters. Recent studies examining the diffusion of complex technology, however, show that it needs to be understood as networked, malleable, and socially constructed (Lyytinen and Damsgaard, 2001; Tuomi, 2002). In addition, these studies show that the diffusion of information technology innovation does not occur in a homogenous and stable "social ether" among autonomous adopters. Instead, the social arena for innovation diffusion is dynamic and volatile, subject to political control. Past research on innovation has also tended to treat innovation as an object (thing) created by a single heroic individual, or a small group of individual specialists, separated from the rest of an organization (Lyytinen and Damsgaard 2001). Therefore, these studies often fail to make a connection to the ongoing process of “innovation” in the everyday work practice in organizations by making a spurious separation between innovation and its “diffusion” and treat the latter as specific singular events.

Information technology impact studies have examined repercussions of “fixed” forms of technology use on organizational structure (Barley, 1986; Huber, 1990; Malone et al., 1987; Orlikowski, 1992), individual behaviors (Bellotti and Bly, 1996; Luff and Heath, 1998; Shneiderman, 1980; Valacich et al., 1994) and firm performance (Brynjolfsson, 1993; Clemons and Row, 1991; Hitt and Brynjolfsson, 1996; Weill, 1992). Some of the past ethnographic studies of the impacts of digitalization on work practices have followed similar goals and / or approaches as pursued here. They have examined the use of digital representations instead of plain printed documents in offices (Wynn, 1979), health care (Heath and Luff, 1996), large public institutions (Harper, 1998) and the paper industry (Zuboff, 1988). The closest example to a similar study as this is Yetton *et al* (1993) who studied the digitalization of an Australian architects office from the view point of strategic and socio-technical change.

These past studies have usually been carried out without taking into account the path-creating occasions which forms of technology adoption offer for organizational change (Orlikowski, 1993; Orlikowski and Robey, 1991; Swanson, 1994). Often, digital representations examined in these studies are treated as mere digital replicas of the earlier representations. The 3D representations under study in this paper are radically different forms of representation that convey and enable construction of new forms of knowledge. Moreover, most of these studies have focused on a single organization, and ignored the impacts of new digital representations on multiple communities of practice within industrial fields. Thereby, these studies have not examined in a longitudinal way how networks of innovation emerge from employing novel digital technologies such as 3D digital representations in an industrial field.

Within the *information technology design studies* scholars have mostly focused on how to model and represent a task domain in order to establish a sound basis for supporting its professional activity using digital representations. Such domain models are thereafter encoded into software, which utilizes and enables new forms of digital representation (Jarke and Pohl, 1995; Weiss and Lai, 1999). The design research seeks to improve the content of digital representations, to analyze occasions of their use as part of a work practice, and to utilize such representations effectively in a new work context. Most of these approaches, however, analyze design processes as singular events of formalization that lead to increased digitalization of work objects. They thereby ignore the continuous interplay between digitalization of representations and new organizational processes and activities that follow their appropriation within a community of practitioners. As a result design research has gained a relatively poor understanding of how initial designs become “redesigned” over time (Orlikowski, 1992) by their appropriators, how such new design knowledge can and need to be fed back to initial design context. In fact, design for digitalization should be understood as a continuous activity which enables communities to create new paths which more effectively utilize their digital representation media. An important recent trend in information system design over the last decade has been a growing recognition within requirements engineering research for taking seriously how work practices relate to future software. Approaches addressing this concern include participatory design (Kyng, 1998), and methods that seek deep understanding of work practices through ethnographic data analysis methods (Button and Harper, 1996; Harper, 1998; Harper et al., 1998; Hughes et al., 1992). Our research draws upon this tradition and follows how requirements related to 3D representations have changed over time within different communities as an outcome of continued appropriating the 3D representations into new design and construction projects.

In information technology design studies, the concept of software product families (Weiss and Lai, 1999; White, 1996) lends themselves for improved service and product evolution. This concept serves as an interesting starting point to study the evolution of the CATIA system. Similarly, Lehman and Belady (1985) proposed the concept of E-program. Such class of programs, by being deeply embedded into the environment by representing a model of it, influence the environment whenever they become part of it, thus leading to a successive expansion and refinement of software functionality. Hence for e-programs functional requirements cannot be fixed beforehand. Instead, they emerge over time as a result of smaller scale prototyping experiments (Gronbaek and Mogensen, 1997), or larger scale experiments of enhancement during maintenance (Boehm, 1988; Swanson and Beath, 1989). Such experimentation is one instance of the path creation/ path dependency dialectics driven by the innovation and appropriation of IT as examined in our study.

A dominant perspective in the research stream of *knowledge work* treats knowledge creation and knowledge reuse in organizational contexts as two separate processes (Huber 1991; Markus 2001; Pentland 1995; von Krogh et al. 2000). This assumes that once knowledge is created by an actor in the community, the knowledge as a black box is transferred in a rather closed and fixed form to the rest of the community for reuse. An emerging body of research on knowledge work, however, emphasizing the importance of communities of practice and communal and emergent features of knowledge creation (Brown and Duguid 1991; Brown and Duguid 2000; Lave 1993; Lave and Wenger 1991; Wenger 1998). It has shown how important an on-going interaction through shared artifacts and practices among the members of a community of practice is to their ability to create and use knowledge. However, most of these studies focus on one community of practice. They leave us with little understanding of how innovations embedded in new representational forms in one community ripple through other, interrelated communities in a network, crossing boundaries between professions and organizations and creating innovations in webs of knowledge in a distributed system (Boland and Tenkasi, 1995; Boland, Tenkasi and Te'eni, 1994).

Building on this emerging perspective, yet critically extending it into multiple levels of communities, we view distributed knowledge in a networked community as being created through the reciprocal dynamism of path dependent and path creating behaviors of these actors that are mediated by new digitized representations. Therefore, we explore the capabilities and aspects of 3D digital technology that enables dynamic knowledge creation processes in a networked community of practice in a construction industry. This helps us articulate patterns of design and "redesign" as knowledge creation and sharing practices, i.e. how to design digital representations so that they either constrain or enable path creation a.k.a. knowledge expansion, and how these designs overtime become an ongoing orchestrated activity, which moves the whole community along as it tries to learn and explore how to exploit the new forms of 3D representations.

In our study, we try to overcome some of the limitations of these streams by studying simultaneously how new ways in which digital technologies have been designed and implemented can lead to multilevel innovations in a set of communities as they adopt new ways to digitally represent and manipulate primary boundary objects of their work practices, and how such experiences lead to new innovations in digital designs and representations. Therefore, we use an historical, process oriented research approach that seeks to conceptualize and account for the observed longitudinal transformations as a result of path dependence and path creation by the key actors in these multiple communities.

The Concept of Path, Path dependency and Path Creation

Path creation is a recent attempt to theorize the process of innovation, which has been developed in reaction to certain limitations in the theory of path dependence. Briefly, *path dependence* grew from the work of David (1985) and Arthur (1989) and brings a dynamic systems view to technology innovation studies. Path dependence argues that history and temporality is important in understanding how technological innovations are adopted. According to Arthur (1989), path dependence is reinforced by large fixed costs, learning effects, coordination effects and adaptive expectations.

Path dependence has been used to show how a seemingly insignificant event comes to have a major impact in the success or failure of a technology innovation over time. Usually, this chance event is from outside the normal field of concern for the technology, and through a series of subsequent events creates a “path dependence” that shapes the probability of moves by actors in the technological domain such that a self perpetuating cycle is established which leads to a technological lock-in. Often, the end state technology is in some sense sub-optimal, and path dependence thereby shows how technology innovation does not conform to rational choice models.

For our purposes, however, path dependency is insufficient alone because it treats the involved actors as lacking agency, and behaving like dumb robots that simply trot along with the established path. Path creation, in contrast, introduces agency into the analysis and focuses on how actors mindfully deviate from what appears to be the common sense, established paths. Instead, they engage in opening a new path of practices and resource use in their domain. The duality of path creation and path dependence can therefore usefully be approached with a structurational view (Giddens, 1984; Lyytinen and Ngwenyama, 1992; Orlikowski, 2000; Walsham, 1993) of duality between structure and action. Following Kemp et al. (2001) and Van Looy et al. (2001), we see path dependency and path creation also as reciprocally related and mutually dependent processes: without path dependency there is no ability to recognize the deviance in path creation, and innovators engage in path creation in hopes of establishing new stable sets of path dependence. Moreover, some forms of path deviation are occasions of restructuring the whole open territory of technologies and work practices in front of the actors to become a new locking springboard for path following. In our view, enhanced digitalization of principal representations in a community can be one such occasion.

Several mechanisms influence the creation of new paths. Dosi (1982) argues that besides market forces, the interaction among scientific advances, economic factors, institutional variables and unsolved difficulties on existing technological paths drives technological “paradigm” shifts. Kemp et al. (2001) examine the role of strategic niche management in creating new paths in the alternative energy development movements in California and Denmark, especially the role of governmental policies, and Van Looy et al. (2001) propose various community-spanning strategies for stimulating path creation. Garud and Karnoe (2001) use the example of entrepreneurs as mindful deviators in path creation.

In our view, the idea of path creation process applies better to the professions of design, especially to that of architecture such as Frank Gehry. In fact, when entrepreneurs or visionary managers engage in path creation, they are necessarily designing. A path is made of expectations, beliefs, work practices, routines, standards, and technological artifacts that operate at the social, institutional and cognitive levels. A designer who engages in path creation must engage in actions, which will affect all these levels in ways that will resonate and reinforce one another. If the he is successful, it will lead to the emergence of a new set of technological designs, expectations, routines, practices, beliefs, etc. Thus, designers all the time engage in a complex, multifaceted process that combines path dependency and path creation as they apply principles of design such as openness, experimentation, exploration, problem finding, and alternative generation.

Path Creation in Architecture and Construction

There are multiple levels of potential path creation and path dependence in the use of 3D representations in the architecture and construction. They include: (1) the development of the 3D software tools and underlying domain models (the digital design path), (2) the changing work practices of architects using the digital representations, (3) the kinds of projects that are designed with digital representations, and (4) the appropriation of digital technologies by contractors and subcontractors. All these levels are interrelated and involve changes in technology use, work practices, knowledge assets, and organizational structures and strategies, which we are trying to understand in holistically in the study of 3D induced innovation as separate moments of path creation.

Figure 3 represents the framework of studying multiple levels of IT induced innovation that result from the use of 3D digital representation. Principally, it is based on two major forms of recursively organized processes of path creation with 3D technologies. First, there is an on-going path creation related to the design of the digital technologies and their appropriation by architects into their design practice. The vertical flow represents this in the figure. Here, the appropriation of new digital technology by an architect enables radically new architectural designs with each project representing unique opportunities for mindful deviation from existing path dependency in architectural forms and the use of 3D representations in architectural practice. Over time, these accumulated experiences form the basis for new designs of digital technology leading to a revised version of the 3D tools and further appropriation in the design practice of architects. This socio-technical design cycle involves levels one, two and three of the multilevel architecture and construction context outlined above.

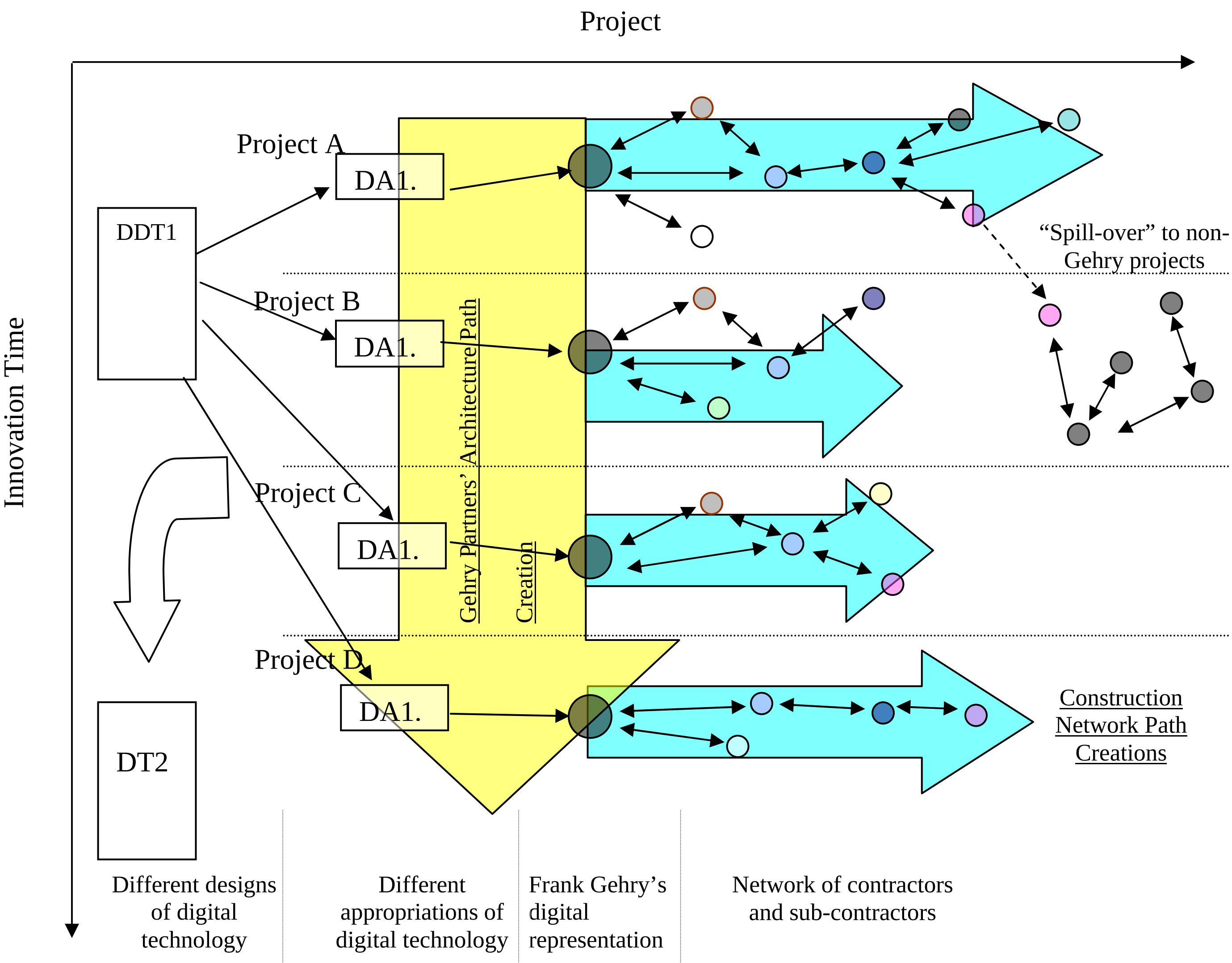

Figure 3. Two Dynamics of Path Creation with Digital technologies: Innovations in Architecture and Construction

Second, there is a cascading path creation in the socio-technical network of the construction community for each project. This is represented in the horizontal flow in figure 3. As each project progresses, the innovation in architectural design enabled and represented in 3D digital technology creates new opportunities for innovation in construction methods and technology appropriation by participating construction managers and contractors. In this cycle, actors in the construction community develop new paths of preferred construction practices. The diagonal dotted line in figure 3 represents a "spill-over" of innovation to other projects by one or more of the contractors. This socio-technical design cycle involves levels three and four of the multilevel process discussed above. Combined together, these two main dynamics of path creation and their interplay in a socio-technical network form the basis of an evolving lattice of innovations across the four levels of the design and construction context.

In order to produce buildings that are cost effective and "buildable", architects normally follow traditional (path dependent) practices as the safest course, including the use of two-dimensional blueprint drawings at each of these levels. However, in order to produce buildings that are as meaningful and evocative as Frank Gehry has done architects, constructors and fabricators must invent continually ideas that are outside of the established design and construction path. As a result new architectural designs will form a constant dynamic reassessment of the material, technological and practice requirements of the known, feasible path. They offer the potential of breaking the familiar pattern of those materials, practices and technologies in order to achieve a higher order "artistic" benefit for the client and society.

We conducted interviews with the architects, construction managers and all subcontractors on the Peter B. Lewis Building project, including visits their home office to review major documents with them. The objective of these interviews were to identify ways in which the various parties found the digital representations used by Gehry partners to be different from their usual documentation and information sharing practices, and the ways that the parties adapted to those differences. We looked for the development of new knowledge assets, the acquisition of new digital technologies, the retraining of existing employees, the hiring of new employees, the restructuring of their organization, and changes in labor practices. These interviews focused mostly on paths (2), how Gehry and his associates changed their work practices while designing and building the Peter B. Lewis building and (4) how the contractors adopted and appropriated 3D representations as necessitated and conveyed by Gehry & associates' practice.

To accomplish this goal we asked first within Gehry and associates how the design and construction of Peter B. Lewis differentiated itself from the earlier projects within the architects' office and what path creation activities were taken during this project. Second we asked consequently multiple contractors and regulators involved in the project to compare and contrast their experience with their Gehry Partners project to other projects they have had in the past few years. We also asked them about projects contracted subsequent to the Gehry Partners building to assess ways in which the changes in technologies of representation, knowledge assets, labor practices, and organization structures or strategies were carried forward into those later projects (spill over effects). We started with a set of initial interviewees, and we updated and expanded that list as we traced the actor network relations and followed path creating choices, and came across additional firms and individuals who also played significant roles in the innovation around Peter B. Lewis building project.

Results

As noted we are address two primary levels of path creation in this study. The first level concerns path creation in an architectural practice as it adopts three-dimensional representations. In this paper, we focus on Frank Gehry and his firm, Gehry Partners on a specific point of time when they were designing Peter B. Lewis building. The second path creation concerns a specific moment in the ways in which that the three-dimensional representations become incorporated into design practices how contractors, subcontractors, architects, consultants and clients get arranged and how they interact in this project as a result of 3D representation potential. An additional level of path creation concerns the contractors themselves and the ways in which they adopt the three dimensional technology into their own construction practices in projects which do not involve Gehry Partners. Their path creation includes changes in the technology use by the contractors, as well as organizational structures and strategies that the contractors adopt, including the changed work practices of their office staff and laborers. We begin our analysis with a general discussion of three-dimensional representation and its impact on construction processes during the Peter b. Lewis building process.

Measurement Dimensions and Three-Dimensional Representations

The use of three-dimensional representations during architectural design differs from the familiar two-dimensional representations of paper drawings in very substantial ways. Though both of them seek to provide an *iconic* representation of the building in the sense that the representation and the actual material object has *some resemblance,* the accuracy and fidelity of the 3D representations as *iconic forms* surpasses enormously those of 2D representations. The major difference is that all object placed in 3dimensional space can be located and proportioned accurately which increases the accuracy of building representations. In a way 3D representation provides a model of the building (though in a smaller scale) how it is actually built. Second, due to increased computational capability the 3D representations can be explored “interactively” from any angle or view point which one wants to adopt in relation to the actual building. Third the representations can be simultaneously scaled up or down to any accuracy which the viewer wants to take. Such iconic “resemblance” and the resulting possibility to “physically” explore the building from different distances and angles is not possible in the 2D representations. Another difference is mathematical qualities of the 3D representations, which enable instantaneous derivation of multiple types of information from the representation including surface properties, structural features, cost estimations (based on 3D forms embedded), and so on. The third difference is that digitized 3D representations allow also for the integration of symbolic information of the represented 3D objects including size, material properties, etc. which can be integrated with subsequent production and planning processes associated with the building.

The impact of using 3D representations spans also construction and especially how the measurements are taken and how the 2D v.s. 3D representations are gradually mapped into the physical building. Traditionally two-dimensional images have a measurement shown for the distance between each corner element in a drawing, as well as between selected lines. Hence, in a traditional, path dependent, 2D representation based construction project each measurement is taken off of the last measurement.

By contrast, three-dimensional images are created by mathematically locating every point on a line or surface in the image with an <x,y,z> coordinate showing its position to an established X=0, Y=0, Z=0 point. So the first major implication for a construction company is that the familiar tape measures and other devices for calibrating distances are no longer needed and a burden. A major implication for a construction contractor is the need to use specialized surveyors for making location measurements within a 3D space that normally would be made by workers with a tape measure in a given 2D plane. Every time the edge of a concrete wall that is about to be poured is set, and every time a hole for a future plumbing fixture is put into the concrete, and every time a steel beam is located, a surveyor is required for the <x,y,z> coordinate to be located. Moreover, each <x,y,z> coordinate is located independently of other measurements, and is made relative to the absolute <0,0,0> point that had been established before construction began and forms the anchor point for the 3D representation of the building.

The result of this shift to using <x,y,z> locations throughout the whole construction process is profound. On a two-dimensional construction project, the minor mistakes and measurement errors that inevitably occur become compounded. If the edge of the concrete wall is set slightly off, and a framed interior wall is then measured in relation to it, a further chance for measurement error is introduced. Then, if the location of an electric conduit is set by measuring from the edge of the framed wall, and a heating duct is located by measuring off of that conduit, the process of compounding measurement errors continues. Each new element of the unfolding complexity of the building is measured with respect to previously measured elements and errors are carried forward at each step. In concrete work, for example, it is commonplace to have pipes trying to go where there are no holes, and to have holes where there is no need for them, etc. On the Lewis Building, even with its highly curved and undulating surfaces, the construction company found that the use of <x,y,z> coordinates increased the accuracy of construction such that the incidence of mistakes which required rework was extremely low. This came with the cost of using a large number of measurement points which could only be managed through computerized means (large Excel files). For example, the inner walls of the building required c.a. 55 000 measurement points by the surveyor where a normal building would have needed between 20 – 30. At the same time the accuracy increased dramatically. As the construction manager put it, they had less concrete rework on their job with 3D representations than they would expect on a typical rectangular, poured concrete parking structure.

Level one: Path Creation in Architectural Practices

A Geneology of Adopting Three Dimensional Representations. A first question is how the Gehry Partners architectural firm came to experiment with three-dimensional imaging in the first place. That story has overtones of a genealogy, in which multiple strands of causal elements come together at a moment in time, making a unique combination out of which new possibilities for organizing social and economic relations emerge. As noted for the architectural firm of Gehry Partners the convergence centered on the 1992 Barcelona Olympics. Gehry had been commissioned to design a pavilion at the Olympic village, and towards the end of the project, a commission to create a giant, building-sized sculpture of a fish to complete the pavilion area was proposed. The fish proposal had many challenging aspects: first, the time remaining before the project must be completed was only six months; second, no design work had been on the fish; third, the fish would undoubtedly be a dynamic sculptural form that would be very difficult to design and build in a short period of time. The elements which came together and enabled the fish to be designed and constructed on time and under budget included the following: (1) an architect with a taste for fluid, sinuous forms that challenged the construction technologies of the day; (2) a new partner had joined the firm, Jim Glymph, who brought with him a taste for pushing technology to its limits and had been thinking about incorporating digital technology into architecture, especially the CATIA three-dimensional system being used in aerospace; (3) a contractor who was not afraid to take risks and was intrigued by the challenge of using emerging technologies and constructing innovative, sculptural forms. Interestingly, each of these three elements rely on an individual, not a corporate body - an individual who clearly had an entrepreneurial drive to explore and create for its own sake. Finally, the setting of the Olympics itself set heightened expectations of doing something memorable and indicative of the best of the human spirit. Having all four of these elements coming together was an important enabling condition for the fish sculpture to be possible. One important contractual feature in this project was that all parties were willing to suspend the normal architect/builder relations of risk allocation and contractual performance requirements. Instead, each of them agreed to an arrangement in which they held each other harmless. The fish was designed and constructed within the six month time limit, and Gehry Partners began to incorporate three dimensional images into their subsequent projects.

Path Creation in an Architectural Practice - Abstract and Concrete Representations. Gehry Partners are a uniquely suitable firm for the introduction of three-dimensional representations for several reasons that relate to their design practices. The firm has always worked differently from other architectural firms in that they use almost exclusively physical models as a basis for their design. Their studio is full of models, with very little paper or drawings to be seen (see figure 4).

Figure 4. Architecture office space of Gehry & Partners

Only after working through literally hundreds of models they make a drawing. So when they began using three-dimensional software, they were able to digitize their physical models and derive their 2D drawings from there as needed. Most architectural firms on the other hand, work with drawings almost exclusively in their design. Only after refining their drawings to a point where they believe their design work to be completed would they make a model and its purpose would be to display their design, not to think their way through the design process. In a normal, two-dimensional architectural practice, then, a model is the end point of their design work, but for the Gehry Partners, three-dimensional models play a central role in their architectural practice. Adopting the three dimensional representations solves a major problem that they had in translating the increasingly complex physical models they created into the two-dimensional drawings required by the standard practice of the construction industry.

Gehry Partners were well aware of the push to integrate computer-based representations into the architectural design process, especially as spearheaded by Professor Thomas Mitchell at

MIT. They had, however, always resisted that attempt to introduce computers into their practice as a 2D drawing tool, fearing that the unique spirit of a design gesture can be lost if the architect works in (and could be constrained by) a computer based 2D system. Instead, Frank Gehry himself works with free hand sketches and physical models made of plastic, paper, tin foil, cardboard, waxed cloth and other "found" materials. He believes that moving between the sketches and the physical models directly is the best way for him to maintain the feeling and evocative power of the sketches. This raises what for us was a counter intuitive aspect of two and three-dimensional representations encountered in the field work. We had assumed that three-dimensional representations, being dependent on advanced computing technologies for their realization, were more abstract and cognitively demanding representations than two-dimensional ones. We have come to discover, however, that it is the two dimensional-representations that are the more abstract and cognitively demanding. The project architect for the Weatherhead project stated:

> *"Remember, in the Gothic or Baroque, they didn't have drawings when they built cathedrals and big palaces. They had very few drawings. They built models. So, I think if we get the 2-D out of the process, everything will become a little more fluid again and a little more interesting. You never have to go through this mental reduction process to cut everything down to 2-D. … And now we are throwing the drawings away and Frank suddenly has the ability – and other modern architects too – to go back to really interact in three-dimensional space. … (It is more) natural. We design in 3-D and we build buildings in 3-D, and that's where we shape all things. We don't have that artificial abstraction layer in between that is drawings." (Gerhard Mayer, July 24, 2002)*

Similarly, the sub-contractor for a sheet metal contractor commented:

> *"The 2-D thing is really the more frustrating part because it's a lot easier to understand in 3-D than 2-D,…"* (Bill Zahner, May 17, 2002, p.13)

Architects and drafters develop the ability to translate three-dimensional objects into two-dimensional drawings and to read those drawings and reconstitute an understanding of the three dimensional object being depicted. People without this unique training generally find it difficult to read two-dimensional images as three-dimensional objects. The Gehry firm with its practice of moving directly from a sketch to a physical model were eliminating untold layers of abstractions embedded in the sets of drawings that most architectural firms work with. By relating the initial sense of form as suggested by Frank Gehry's unique "stream of consciousness" sketches directly to a physical model, they were avoiding abstraction in favor of concreteness and immediacy. Gehry Partners was concerned that introduction of software tools into their design practice would threaten the close link between Frank Gehry's design inspiration and its realization in a final design. The three dimensional software showed them that computers could be integrated into their practice in a way that complemented their existing approach and solved a nagging problem for them - the problem of translating physical models with complex geometries into the two-dimensional drawings expected by the industry.

> *"What it meant was that Frank worked in medium that allowed him to quickly understand things as three-dimensional. But it also gave him a medium that*

allowed him to walk a layman through his own thought process and his own design process and get them to understand it and get them to participate." (Jim Glymph, July 24, 2002, p.3

As more flexible three-dimensional tools such as Rhino are becoming available, Gehry Partners have begun experimenting with preliminary sketches made in these simpler systems as communication devices with contractors and clients during early stages of the design process. It remains to be seen how far they will go in incorporating software tools into the design process, but philosophically, they are committed to the use of physical models as the medium for exploring design ideas, employing the three dimensional software tools to supplement the physical experience. At that point in the process, systems like CATIA or Rhino enable them to specify how the complex structures they have designed can actually be built or to develop a better physical model of the developed 3D model - something that the physical models cannot accomplish for them.

Frank Gehry and his partners are quick to point out that they do not believe the use of three-dimensional representations has altered the basic spirit of their designs. That is, they do not believe that they have been able to conceive of more complex shapes or different types of architectural forms because of their use of three-dimensional software. Their imaginations have always outrun their abilities to represent their ideas. They do, however, believe that the complex and dramatic forms they have been able to achieve in their recent designs are only buildable because of the three-dimensional tools available to them. Without the tools for visualizing and analyzing these structures in three dimensions, they could not have worked out all the details required for specifying how the structures were to be built. So while they hesitate to attribute the gestation of ideas to the software systems, they do recognize that it gives them a certain confidence in what they can try to accomplish in projects facing them. The limits of what they can conceive and feel confident of being able to build has expanded with the use of three-dimensional representations, resulting in a positive feedback cycle of ever more daring structural forms in their architectural practice.

"Catia makes the whole process to build it somewhat predictable. And that's what all our processes are looking for. We give prices before we build…if you need to predict, if you need to give somebody… a guaranteed price that you will not exceed, you cannot do this (with 2D). Because it is too complicated to document on paper. Without CATIA it would have not been possible to do it (the Lewis Buiilding)." (Gerhard Mayer, September 20, 2002, p.8)

Level Two: Path Creation with Three-dimensional Software - Feedback to Developers

The second level of path creation is centered on the three-dimensional software itself. Because the software system Gehry began using was originally designed for the aircraft and automotive industries, it had to be adapted to the requirements of an architectural practice. We find that the both the Gehry Partners firm as well as certain subcontractors invested substantial effort in creating software modules to use in conjunction with the CATIA system. These modules provided an interface between the existing CATIA system and the practices unique to the architectural and construction industries, enabling them to use the software effectively in their own settings. Gehry Partners benefited by being a high profile adopter of the CATIA software. IBM, who had purchased Dassault Systemes, took considerable interest in Gehry's use of the software. IBM would use the Frank Gehry studio as type of sales platform to encourage other non-aircraft manufacturers to consider bringing the CATIA three-dimensional software into their professional practice. One of the first contractors to work closely with Gehry Partners was A. Zahner and Company, a sheet metal specialty contractor located in Kansas City, Missouri. They also were early adopters of the CATIA system, although they also experimented with other three-dimensional software, especially as parametric models that included more information about each component of an image (such as its relation to other components, its cost structure, etc.) became available from other software developers. Whereas Gehry Partners developed their own software tools to help them integrate three-dimensional software capabilities into their architectural work practices, the Zahner Company developed tools which enabled their metal forming and cutting machinery to be driven by a the output of the three dimensional models.

Both Gehry Partners and Zahner Company fed knowledge of their own software developments and their desires for future enhancements of the CATIA system back to IBM and Dassault, including the kinds of features and capabilities that they needed in the three dimensional software to be most effective for their purposes. As of this writing, Gary Partners are in the process of establishing a joint venture with IBM in order to create a version of the CATIA System that is specifically designed for the architectural and construction industries. In this joint venture, the software will have embedded in it an approach to the management of architectural projects that reflects the unique, path creating forms of practice that have evolved in the Gehry Partners Firm over the past decade. So the three-dimensional imaging system that Gehry Partners originally adopted from the aerospace industry 10 years ago is about to become an integrated tool for architectural practice reflecting the unique project management techniques developed by Gehry Partners.

Level Three: Path Creation in Construction Projects - Loose and Tight Coupling

In studying the projects of Gehry Partners, one important aspect of the role of representations stands out. The 2D representations used in an industry's standard practices, are an integral part of the entire relationship between the architect, the builder the contractors and the client. The representations they pass among themselves are communications that are integrated with and rely upon the context of all the business practices, contractual forms, and traditions that characterize their industry. A change in the representations they use also changes many other aspects of their relationship. One image that has been very helpful to us in thinking about the relation of representations to the relations among architect, client, builder and contractors is that of loosely coupled versus tightly coupled systems. Over time, using two-dimensional representations, the architects, clients and builders have established patterns for creating and exchanging 2D drawings that included understandings of the timing for exchanges, the responsibilities of each party after an exchange, and the way that risks are allocated among the parties.

The two-dimensional representations are enmeshed in a loosely coupled system. Each party can take the architect's drawings and rework them into their own preferred way of viewing the project, and can come back with a bid or a request for information. There is very little need for the architects, builders and sub contractors to meet and discuss details of the project. The representations carried the information they expected to need in order to perform their next step in the process. The contracts were written with two-dimensional drawings and the level of information that they could carry taken into account. So, the normal two-dimensional process of representation includes a significant amount of document origination within each of the separate firms. We picture the firm's in a large construction process fitting together as a loosely coupled system in the sense that they can rely upon a rather minimal amount of information being transferred among the parties in a standardized format because contractual understandings and industry practices allow each party to develop their own specifications for fulfillment of their obligations. The project architect commented on the traditional relationship between the architects and contractors as follows:

> *"With typical projects, many architects have a standoff position from contractors. They just basically enforce their documents and their specifications and criticize. And they expect that the contractor knows how to do everything. …. At the big firms, they run around in suits, they run around the construction sites with big books, they write reports, write a lot of memos, it's not a very interesting task many times." (Gerhard Mayer, September 20, 2002, p12)*

Similarly, a senior partner at Gehry Partners office commented:

> *"What architecture's generally done is move away from taking more responsibility. In fact, the schools and the insurance companies have encouraged them to. You have the profession set up so that you don't take responsibility for how the building's built, right, that's the contractor's job. So basically, the profession has moved away from that kind of broad base, and it's going to take a lot to solve the problem. Software is a start but it is going to take a whole generation to bring the profession back again." (Jim Glymph, November 9, 2002, p.6)*

When the two-dimensional representations are replaced with three-dimensional ones, we find that the familiar contract language and the established informal working arrangements that have evolved in the construction field do not provide a contractor with sufficient information to understand their role or with a sufficient understanding of the risk involved. And this is the case even though in many ways the three-dimensional representations carry much more information than the two dimensional images do. It is because the formal contractual relations and the informal working arrangements in the construction industry are inseparable from the type of representations being exchanged.

Changing to a three-dimensional drawing changes many other features of their relationship as well, further creating a more tightly coupled system. The architects, builders and subcontractors had to meet and talk about almost every detail imaginable. A dramatic example of this comes from GQ Contractors, the plaster and drywall subcontractor on the Lewis Building project. Their Chief Operating Officer reports that in his 20 plus years of work in the industry, he had perhaps spent the equivalent of one 8 hour day in an architect's office. Normally, they would receive drawings, analyze them to make a bid, rework them as shop drawings in their own office, and do the work. On the Lewis Building project, however, he spent the equivalent of 17 weeks in the architect's office, working with three-dimensional modelers to plan how the framing and drywalling could be done.

> *"I have never, ever spent more than an hour in an architect's office prior to this job. And I spent 22 trips, 4 and 5 days at a time in their office. And I spent some days where I was in there at 8:00 in the morning and I didn't get out of there until 10 or 11 at night, working on this frame." (Ed Seller, September 18, 2002)*

Similarly, the organization of the overall project was more tightly coupled, with the general contractor and certain key subcontractors brought into the process at the very beginning of the planning phase, rather than after the design was complete, as would normally be the case. Part of this increased tightness in coupling is due to the fact that the three-dimensional representations enabled the architect to create designs with unusual and demanding geometries that the builders were not used to constructing and needed to discuss. But apart from that, the three-dimensional representations carry different information than the familiar two-dimensional drawings do, and construction practices are based on the information in the familiar two-dimensional drawings. In the future, three-dimensional representations are likely to engender even more tight coupling as they become more fully parametric and capable of containing cost, construction time, and other information for each element of the representation. Theoretically, the three-dimensional representations could carry all the information needed by all the specialty contractors - information that they previously had to create by themselves from the architect's drawings by making their own, customized set of shop drawings to use as a basis for their construction work. We anticipate that the level of coupling in the system will decrease from the intensely tight coupling we see on the Lewis Building project, but we also anticipate that the ability of parametric, three-dimensional models to link across all parties with a single representation to result in a tighter coupling in the industry than exists with the current two-dimensional representations. A sub-contractor's comment reflects this tight coupling well:

> *"And understand we're breaking down this whole wall. It used to be like this: Zahner has this concrete wall separating the shop from the office. Then all of a sudden all the people in the shop are coming in here (the office) mixing in with engineering people and mixing people from the trade and so it's kind of like, tear that wall down." (Bill Zahner, May 17, 2002, p.2)*

Level Four: Path Creation in Contractor Firms - Expansion and Technology Leadership

We focus on two firms involved in the Lewis Building project for this discussion of path creation in subcontractors. The first subcontractor we will consider is GQ Contractors, the dry wall and framing subcontractor on that project. Before we had mentioned how the Chief Operating Officer of that firm worked much more closely with the architects than had been his experience on any previous project. But the impact of working with Gehry Partners on the Lewis Building project goes far beyond tightness of coupling in their day-to-day experience on the job. First of all, the intense involvement with three-dimensional modeling led them to develop skills in the use of three-dimensional modeling in making more accurate estimates of the costs of construction, especially on more complex projects. This skill has led to their being asked to participate as a consultant to local drywall framers in other regions of the United States where Gehry Partners are working on other projects. Up until the Lewis Building project, they were a north east Ohio contractor, but afterward, the are becoming more national in scope.

> *"And we have bid the Founders Room at Disney Concert Hall in LA, and we are looking to participate at MIT. Now Dan Sieb of Hunt has contacted me, he's*

actually looking for us to provide budgets so he can work numbers on the Princeton job, and we definitely would like to partner with somebody on Princeton. But there again, we want to work the technology side more so than having guys on the field actually install it. So that's how we would like to partner with local contractors. ….we've never done that type of (consulting) work." (Ed Seller, September 18, 2002)

The strategy of the firm has also changed as the Lewis project introduced them to new materials and processes. One unique aspect of the Lewis Building was a series of very large volume classrooms. These classrooms were not large in floor space, but they had very high ceilings, sometimes 35 ft. or more. The acoustics required in a classroom are very difficult to achieve with such large interior volumes, in which voices bounce and reverberate. This led to a search for new materials that could be used for sound absorption in those rooms. The standard way of sound control would have been to install large sound absorbing panels on the walls and ceiling. But the walls were highly curved and the sound absorbing panels could not have conformed to the curved shapes of those walls effectively. In conjunction with the architects, a new product was identified in Europe (Baswaphon) that is a special type of highly sound absorbent plaster. It had only been used and the United States on any a very limited basis. GQ established a relationship with the U.S. agent for the Swiss manufacturer, and became the licensed installer where for the twenty states in the Eastern United States. At the time of this writing, construction projects using the German plaster material are just beginning, but the contractor has a backlog of jobs working into 2004. They are establishing offices in key cities east of the Mississippi River, and are transitioning to a larger scale of operations than anything they had envisioned before their involvement on a Gehry Partners project.

"We've become the biggest Baswaphon sellers in the United States. We actually have territorial rights from Chicago to New York to Miami. We have 20 states within our territory. We are the exclusive sellers. So this has created a whole division of our company. Now that doesn't have anything to do with 3-D but it has to do with their innovation and their willingness to try new things. It's what it's done for us." (Ed Seller, September 18, 2002)

Our second example, the A. Zahner Company of Kansas City, reflects a more prolonged and enduring relationship with Gehry Partners. Zahner has worked with Frank Gehry on over 20 projects during the last 15 years. It is interesting to note that they first started to work with the Gehry Partners when the Sheet Metal Industry Association was celebrating its one hundredth anniversary and had commissioned Frank Gehry to design a metal sculpture for the center of the hall where the celebration was being held. The association searched for a member firm that had experience in working with architects, and Zahner was one of the only ones who had such experience. So their history of tighter coupling served to open a new possibility for them that has proved to be remarkable fruitful.

The first impression up one receives when touring the Zahner plant is the remarkably thorough going adoption of three-dimensional images and that they have achieved. Their office uses three-dimensional representations for almost every job they perform, whether it is for Gehry Partners or whether it is for a more traditional architectural firm. They also use three dimensional software to control the metalworking machines in their plant. When the workers have a question about how the details of some job are to be executed, they view three dimensional images, not paper drawings. The work orders which had previously been voluminous are now just a single sheet of paper referring to details found in the three dimensional representations.

> *"There should just be the three-dimensional model. Submit that to the architect and then that is what puts out all the shop tickets automatically. And we do it on some of the stuff digitally, so we don't even prepare another drawing…. We also produce two-dimensional drawings right now, which to me is a waste of money and time. But there are certain functions within the building industry that can't work from a (3D) model, they need to see the two-dimensional drawing even though on some work, they're useless." (Zahner, May 17, 2002, p.2)*

When they were faced with the practical difficulty of developing enough operators for the three dimensional imaging technologies who were skilled at both metalworking and also with computer technology and advanced applications of three-dimensional imaging, the company brought experienced union sheet metal workers into the office and trained them to be software operators. This is a most unusual situation in American construction industries, to have any union member be an active part of management, but they have gone even further that that, and have made one of those union operators a project manager. This individual still maintains his union membership, but now also is clearly a member of the management team, directing company projects. The Zahner Company was a subcontractor on the Experience Music Project and for that job, they consciously tried to minimize the amount of two dimensional, paper drawings used in the field. Instead, they installed three-dimensional workstations in their construction trailer so that workers on the site could visit the trailer and access the three-dimensional images for details of how an element they were concerned with was to be constructed.

The penetration of three-dimensional representation into the Zahner Compnay operations goes beyond anything that we had expected to see it on this project. In some senses, they have taken the use of three-dimensional representations even further than the Gehry Partners have. To cite a brief example, Gehry Partners uses the Catia software system to rationalize curved surfaces so that they become "rule developed" surfaces. This means that even though the surface is curved and may appear to be very complex, it is always possible to lay a straight line across the surface. Imagine if you will a collapsible hand held fan. Open it, and put pressure at the point where the many framing members of the fan come together in your hand, and you will create a curved, cone-shaped surface. That it is essentially the principle of a rule developed surface. Such a surface enables complex shapes to be deconstructed into simpler elements and makes those shapes buildable with straight pieces of metal framing (stick building), but it also requires a substantial labor effort in the field to properly locate the ends of each framing members as they fan in and out in a very complicated way over a large undulating curved surface. This was the technique of roof construction used on the highly curved metal roof of the Lewis Building. Gehry Partners had assumed that this same technique would be used on a project following the Lewis Building. However, in discussing their plans for that project with Zahner, they discovered that Zahner had gone further with three dimensional construction techniques for curved metal surfaces. They had developed methods for mass customization of framing members so that framing members themselves were no longer straight, and carried the curved shape in each framing member. That means that rather than having the ends of the straight framing members fan in and out to create curved surfaces, the individual framing members were located at equally spaced intervals along the edge of the surface being constructed. This dramatically reduced the labor cost of installing the curved metal surfaces on the construction site.

> *"Now yeah, the thing that shocked them was that we said we don't want to stick build it, we want to make curved fins, that was, I know Mark (the project architect) commenting at the time, it was like, really? You want to do it that a way? Isn't that expensive? It's like, it would have been at one time." (Miller, May 17, 2002, p.12)*

The Zahner Company has also taken the collaborative, early design stage interactions that Gehry Partners employ on their projects, and has pushed that further as well. The early use of contractors in a design phase of a construction project is sometimes referred to as a "design and build" system. In this system, the subcontractor is paid to work with the architects on the design process, and it later negotiates a separate contract for working on the construction process itself. Because of the there growing reputation as a firm able to complete a very complex metal work project successfully, the Zahner firm is often asked to be involved very unusual cutting edge projects with metal. In these projects, they have instituted a pre design and build relationship that is more like a research project than a design or construction project. In this type of pre design relationship, they work with an architect to develop the kinds of metal working techniques that are needed for a desired effect. Only after the project of technique development and materials experimentation, do they enter into a design and build process to work out more detailed feasibility in applying new techniques to a particular project.

Conclusion

The process of innovation we are tracing through this network of actors in the architecture and construction industries presents a unique image of path creation at multiple levels. Software developers, an architectural firm, a sequence of remarkable building projects, and contractors who evolve as far and fast as the architects are all entangled in a dynamic network of innovation. It is not so much a question of a particular technology being adopted by a firm or group of firms as it is a question of changes in the relationships, work practices, organization structures and strategies that are stimulated by various aspects of three dimensional technologies. Driving it all is a design vision. For Gehry Partners, it is the design vision of Frank Gehry himself. For the contractors, it is a design vision of their firm as leading a craft in its development. All the players in this complicated system have the path creation impetus of an entrepreneur. They are all intrigued by the possibilities of the new and of pushing their expertise into new realms. The design urge to create something different and better than what has gone before is a central element in this web of innovation we are tracing around three-dimensional representations in architecture and construction. The design urge to make each project different from and more advanced in its use of materials and technologies than those which have gone before underlies the achievements of each company in the network. Design, then, is a kind of propelling force - a path creating energy that resonates with a wake of innovation rippling out from each part of the network as they strive to achieve the possibilities that lay in three-dimensional representations.

"Because the format in which these documents was put together on this job did not complete the design, and we found ourselves completing the design. So being that this was a magnified case of that, now we're paying more attention to the design of the other jobs to see where the architect left off so that we can address design issues early on, because a big problem here was the incomplete design. The shape was there, we always knew the shape, but we didn't know how we were going to create it because the documents didn't fulfill all, they didn't cover all the problems. And that's what they ran into in the field, was that they had this set of documents that they typically would use and it would tell them everything where they didn't have it. And so even the carpenters in the field became part of the design, because they had to figure out ways to do things….Actually, they had to help complete some of the design as far as structural elements." (Ed Seller, November 11, 2002, p.13)

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