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SYSTEMIC RISK, INFORMATION TECHNOLOGY ARTIFACTS, AND HIGH RELIABILITY ORGANIZATIONS: A CASE OF CONSTRUCTING A RADICAL ARCHITECTURE

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Abstract

“The test of a first-class mind is the ability to hold two opposing views... at the same time and still retain the ability to function.” (F. Scott Fitzgerald)

In distributed, complex socio-technical systems, risks increasingly originate from multiple sources, affect multiple agents in diverse ways, and thus become systemic. The traditional linear causal model of risk control and an individual decision-maker orientation is no longer adequate to contain such risks. This paper reports a detailed case study of a highly complex architectural project by the architect Frank Gehry and his firm Gehry Partners, L.L.C. Gehry and his partners successfully used the 3D representation software Catia to construct radical architectures with dauntingly complex geometric surfaces in spite of increasing systemic risks. Our findings suggest that, in order to successfully combat such risks, organizations rely upon organizing mechanisms characteristic of high reliability organizations (HROs). Our analysis also indicates that creating and maintaining a collective mindfulness is critical for risk control and mitigation in complex socio-technical systems. IT artifacts such as Catia, in combination with other social/technical elements such as skilled workers, contracts, and communication protocols, can enable the five cognitive processes underlying collective mindfulness: preoccupation with failure, reluctance to simplify interpretations, sensitivity to operations, commitment to resilience, and under-specification of structures.

Keywords: Risk, systemic risk, high reliability organizations (HROs), distributed socio-technical systems, complex systems, mindfulness

Introduction

As information technology innovations become deeply enmeshed into our social fabric, the issue of risk is gaining a new significance. The recent massive blackouts and computer virus attacks are chilling reminders of the Three Mile Island event (Perrow 1984). In distributed, complex socio-technical systems, risks increasingly originate from multiple sources, affect multiple agents with divergent perspectives, and thus become systemic. IT risks increasingly mix with other socio-technical risks, and are dynamically shaping and being shaped by a network of relationships across time and space. Based upon research on high reliability organizations (HROs), in order to successfully control/mitigate risk in complex systems, organizations rely upon organizing mechanisms characteristic of HROs, one of which is “collective mindfulness” (Weick and Roberts 1993; Weick et al. 1999). However, such organizing mechanisms require both hierarchy and decentralization simultaneously and are costly to achieve. We posit that IT artifacts, in combination with other social/technical elements, enable HRO organizing mechanisms such as collective mindfulness.

Our argument is based upon a detailed examination of how risks are controlled or mitigated in a highly complex architectural project by Frank Gehry and his firm Gehry Partners, L.L.C. Gehry and his partners used the three-dimensional representation...
software Catia tactically in order to construct the complex geometric surfaces on the Peter B. Lewis Building at Case Western Reserve University. Involving actors from a diverse set of organizations, an architectural project is a complex and distributed socio-technical system. Numerous risks are faced, concerning such issues as constructability, professional liability, and vendor management. It is an even riskier endeavor if the goal is to design and construct a radically new type of building with dauntingly complex geometric surfaces requiring new construction technology. The insights we gained from this case study provide a basis for theorizing about systemic risks in complex socio-technical systems mediated by IT artifacts. This paper contributes to the understanding of IS software risk management because constructing a building is sufficiently similar to developing a complex software system. In fact, we have argued elsewhere that architecture serves as a better metaphor than economics for information systems design (Boland 1979, p. 268).

Theoretical Framework

Prior Research on IT Risks

Current IS research on risk control strategies concentrates on software development projects (Barki and Rivard 1993; Barki et al. 2001; Drummond 1996; Heng et al. 2003; Keil 1995; Keil and Robey 1999; Lyytinen et al. 1996; Ropponen and Lyytinen 2000; Schmidt et al. 2001; Sumner 2000). Most of these studies look at risk from an individual decision maker’s point of view. Drawing upon various theories, risk factors are identified and their consequences evaluated, and techniques and heuristics are offered to mitigate them. During the process, a single view of risk, usually that of experts such as the project leaders (Barki et al. 2001) or IS auditors (Keil and Robey 1999), is elevated and reified. For instance, although recognizing that different actors may see different aspects of a single risk, the Software Engineering Institute’s (SEI) approach relies upon group leaders to prioritize risks and create risk control and mitigation strategies (Williams et al. 1997).

A review of the IS risk literature indicates the following. First, almost all IS research emphasizes the adverse effects of risk, although it is well-known that risk taking is one of the competitive advantages of an organization (Singh 1986). Second, most research has not gone beyond identifying risk factors to look at risk and control strategies at a behavioral level in socio-technical systems (Schmidt et al. 2001). Third, most IS research on risk focuses on a project within a single organization while considering external stakeholders as environmental factors (Alter and Ginzberg 1978; Boehm 1991; Drummond 1996; McFarlan 1981; Ropponen and Lyytinen 2000; Sumner 2000). Although the stream of research on IT outsourcing sometimes takes an industrial or ecological perspective, the main focus is on make-or-buy decisions (Gopal et al. 2003; Jurison 1995; Lacity and Willcocks 1998), and dyadic relationships between an organization and its software vendors. However, as IT increasingly becomes an infrastructure technology (Carr 2003) and is intimately intertwined with an organization’s operations, the relationship between IT and risk gets more complicated. As Clemons et al. (1995) indicated, IT enabled reengineering changes the risk profiles of firms as they experience IT-associated organizational change. Therefore, IS risk researchers need to look beyond the functional project level risks and understand how risks emerge and are contained in larger socio-technical networks in which an information system is embedded.

Complex socio-technical systems are characterized by “interactive complexity” and “tight coupling” (Perrow 1984), and are increasingly subject to systemic risk. We define systemic risk as a risk that originates from multiple sources, affects multiple agents and propagates quickly among individual parts or components of the network. The probability of breakdowns at the system level can be caused by a domino effect triggered from a sudden unexpected event (Kaufman and Scott 2003). Since the source of a systemic risk cannot be pinpointed and often resides in the unpredictable interactions among different parts or components, systemic risks cannot be addressed by controlling or mitigating the top 10 risks identified by periodic risk review meetings based on group consensus (Williams et al. 1997).

Prior Research on High Reliability Organizations

A complementary stream of research that focuses on risk control in complex socio-technical systems are theories of high reliability organizations (HROs) (Bigley and Roberts 2001; Roberts 1990; Waller and Roberts 2003). HRO research has traditionally studied a single organization operating high-hazard technologies such as a nuclear power plant, nuclear aircraft carriers, air traffic control, and emergency response units. Such organizations are characterized by complex interactions and tight coupling, which create systemic risks. However, they are capable of producing “collective outcomes of a certain minimum quality, repeatedly” (Hannan and Freeman 1984) even in fluctuating and unpredictable work conditions (Weick et al. 1999). Recently, several researchers (Grabowski and Roberts 1999; Ramanujam and Goodman 2003; Vogus and Welbourne 2003; Waller and Roberts 2003) have
pointed out the significance of HROs for mainstream organizations. Weick et al. (1999) call HROs “harbingers of adaptive organizational forms for an increasingly complex environment” (p. 82). With IT-enabled global alliances, rapidly decreasing product life cycles and disruptive innovations, organizations find themselves having to make decisions under tremendous time pressure with limited information where any error could cause potentially disastrous consequences. Therefore, organizations increasingly become reliability-seeking: continuously and effectively staying ahead of competitors and technological obsolescence through vigilance and intense innovation in an extremely unpredictable and fluctuating environment (Vogus and Welbourne 2003). In order to sustain a complex socio-technical system in the face of systemic risks, we posit that organizations rely upon organizing mechanisms characteristic of HROs. However, HRO research to date has not provided substantial empirical evidence on how high reliability principles could apply to mainstream organizations, with the exception of Vogus and Welbourne’s (2003) study of IPO software companies. Studying radical architectural projects can carry their effort further. Less “exotic” and less “far out” (Scott 1994) than software companies in an ephemeral dot-com culture, they provide us with an interesting case about how organizations embedded in a tradition-bound industry came together and achieved exceptional accomplishment by becoming reliability-seeking (Vogus and Welbourne 2003).

Concept of Mindfulness

To sustain a complex socio-technical system in the face of emerging systemic risks, Weick and his colleagues (1999, p. 105) proposed one critical HRO cognitive mechanism: collective mindfulness—the heedful interrelations of activities among social actors—which, if carefully and richly configured, can “both increase the comprehension of complexity and loosen tight coupling.” Five collective cognitive processes contribute to the creation and maintenance of collective mindfulness: preoccupation with failure, reluctance to simplify interpretations, sensitivity to operations, commitment to resilience, and underspecification of structures. These processes “create a rich awareness of discriminatory detail and facilitate the discovery and correction of errors capable of escalation into catastrophe” (Weick et al. 1999, p. 81).

However, risk control in HROs is inherently paradoxical: managing interdependence requires hierarchy while coping with environmental uncertainty requires pushing decision making to lower levels (Perrow 1984; Roberts 1990). Such inconsistent requirements consume a good deal of organizational energy and are difficult to achieve. Perrow (1984) compared this paradox to “Pushme-pull-you out of the Doctor Dolittle stories,” a beast with heads at both ends that wanted to go in both directions at once (p. 331). Employing a “logic of opposition” (Robey and Boudreau 1999), we believe that once embedded in the socio-technical network, information technology can simultaneously contribute to both centralization and decentralization poles of the HRO paradox. The computing capability of information technology enables actors to better comprehend complexity, and its ability to bridge time and space helps to loosen up tight coupling.

The purpose of this paper is to examine how organizations rely upon organizing mechanisms of HROs in order to combat emerging systemic risks, and how IT artifacts, in combination with other social/technical elements, contribute to enabling one critical HRO mechanism: mindfulness (Weick and Roberts 1993; Weick et al. 1999).

Case Study

Research Setting

We conducted an in-depth case study of the design and construction of the Peter B. Lewis Building at Case Western Reserve University developed by Gehry Partners, L.L.C. For the purpose of generalization, we are also following several other Gehry
projects at Massachusetts Institute of Technology, Bard, and Princeton. Our analysis necessarily refers to some of Gehry’s earlier projects as well. The case study approach is consistent with our intent to theorize in an area with relatively little prior research and theory (Benbasat et al. 1987).

The architecture projects by Gehry Partners are perfect natural settings for studying risk control in complex systems. First, Frank Gehry is recognized as an especially innovative architect who has been constantly pushing the envelope in creating new forms of buildings that challenge conventional wisdom. He embraces risks by experimenting with new materials, information technologies, construction techniques, and ways of organizing. At the time of writing, the Lewis Building is one of the most complex architectural designs in the world. Second, architectural projects tend to involve multiple actors from different communities, which focuses our attention upon issues across communities instead of focusing only within a single organization. Although Gehry’s firm is self-consciously at the cutting-edge, many of the contractors are from tradition-entrenched parts of the construction industry. This gives us a unique case for connecting mainstream organizations with the exotic (Scott 1994) HROs. Third, Gehry is the first architect to use Catia, the 3D representation software, not only as a design tool but an organizing tool to construct buildings. This provides us with an ideal chance to examine the role of information technology in sustaining a complex network that accomplishes high risk tasks.

Catia was originally developed in the aerospace industry to resolve and build the complex surface geometries of jet aircraft. Technical features of Catia include full visualization, simulation (structural and stress tests), digital pre-assembly (digital integration of components), and coordination among multiple actors (Baba and Nobeoka 1998).

**Method**

Data collected include interviews, documents, published reports, visits to participants’ home offices, and onsite observations of the on-going projects. Altogether we conducted over 50 interviews with the key actors such as architects, the general contractor, contractors, subcontractors, consultants, users, fire inspectors, and the local city planning commission. We entered the field with the intention of studying IT-enabled innovations and risk taking immediately emerged as a predominant theme in our interviews; it was mentioned virtually by every participant. We asked our participants to contrast and compare how risk and risk perceptions differed in Gehry’s projects from other conventional architectural projects they have had in the past few years. We also identified different risk control and mitigation strategies pursued explicitly or implicitly by actors in the network. Our analysis of the data revealed that Gehry’s firm and their partners exhibited collective mindfulness. Based on that insight, examples of the five cognitive processes underlying mindfulness in our data were identified independently by the authors. The triangulation among the different readers was designed to “bring a different and possibly a more objective eye to the evidence” (Eisenhardt 1989, p. 538).

**Findings**

Our data reveals that in order to successfully control or mitigate risk in complex systems, organizations rely upon organizing mechanisms characteristic of HROs (summarized in Table 1), and that IT artifacts such as Catia, in combination with other social/technical elements, enable the five cognitive processes underlying collective mindfulness (summarized later in Table 2).

**Radical Architectural Projects as High Reliability Organizations**

Traditional architectural projects are loosely coupled, low reliability organizations. Their task requirements are usually standardized buildings of simple shapes and straight lines with standardized materials. Their operating conditions are stable: construction demands are fairly stable and there are easy substitutions for both the standardized materials and skilled builders. Architects, clients, and contractors conduct business

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**Table 1. Traditional Project vs Gehry’s Project**

<table>
<thead>
<tr>
<th>Traditional Architectural Project</th>
<th>Gehry’s Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Low Reliability Organization)</td>
<td>(High Reliability Organization)</td>
</tr>
<tr>
<td>Simple task</td>
<td>Interactive complex task</td>
</tr>
<tr>
<td>Standardization</td>
<td>Non-standardization</td>
</tr>
<tr>
<td>Black box</td>
<td>Tight coupling</td>
</tr>
<tr>
<td>Stable environment</td>
<td>Dynamic environment</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Reliability</td>
</tr>
</tbody>
</table>

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Table 2. IT Artifacts Enable the Five Cognitive Processes Underlying “Mindfulness”

<table>
<thead>
<tr>
<th>Mindfulness</th>
<th>Paradoxes</th>
<th>Organizational Mechanisms</th>
<th>Catia Attributes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preoccupation with failure</td>
<td>Opportunity vs threat</td>
<td>Structural/stress test</td>
<td>Password Layers Embedded information</td>
<td>Make risk vivid vs Hide information</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Password Layers</td>
<td>Embedded information</td>
<td></td>
</tr>
<tr>
<td>Reluctance to simplify interpretations</td>
<td>Diversity vs common understanding</td>
<td>Design-assist Gehry sign-off</td>
<td>Simulations Layers Visualization 2D extracts</td>
<td>Different actors/visual styles Alternative perspective</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Central database Simulations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensitivity to operations</td>
<td>Parts vs whole</td>
<td></td>
<td></td>
<td>Global vs local information Make explicit interactions among different parts</td>
</tr>
<tr>
<td>Commitment to resilience</td>
<td>Centralization vs decentralization</td>
<td>Contract Communication protocol</td>
<td>Simulations</td>
<td>Correct errors on the fly</td>
</tr>
<tr>
<td>Underspecification of structures</td>
<td></td>
<td>Wire-frame model XYZ measurements</td>
<td>Control key points while leaving others open</td>
<td></td>
</tr>
</tbody>
</table>

transactions according to industrial practices, contracts, and traditions which reduce the need for the actors to meet face-to-face to discuss details of the project. Although conventional large-scale projects such as skyscrapers are complex, they are simple in term of interactive complexity. The risks involved can be easily addressed by division of labor, professional liabilities, and black-box processes with little vertical integration across different phases. As a result, architects have been more and more removed from the construction process. It is a common practice that the architect simply throws the design “over the wall” and then leaves it up to the subcontractors to develop their own specifications for actually finishing the building.

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. They don’t talk about process. They just talk about results. Architects run around and measure.

(Interview with Gerhard Mayer, Project Architect, Gehry Partners, September 20, 2002, p. 11)

In fact, the construction industry is among the most fragmented industries in the world (Zielinski and Alampi 2000). In the end, following contracts and industry norms, traditional architectural projects can achieve great efficiency without worrying about reliability: Reliability takes care of itself.

By contrast, in Frank Gehry’s projects, reliability can no longer be black-boxed. Instead, reliability is a mindful achievement of a carefully knit socio-technical system that exhibits HRO characteristics. Gehry projects are tightly coupled in both organization and environment relations and within the socio-technical system itself according to the criteria identified by HRO scholars (Perrow 1984; Roberts 1990; Vogus and Welbourne 2003):

(1) Resource dependence (limited substitutions). Due to the complexity of the building, only a limited pool of subcontractors have the design and fabrication capability required for the job and a handful of clients with the money and vision to embark on such high risk projects.

(2) Time dependent processes. Traditionally, different phases of an architectural project are largely sequentially interdependent, the next phase using the prior phase’s outputs as its own inputs. Due to increased complexity of Gehry’s projects, the interactions among different actors are becoming reciprocally interdependent (Thompson 1967). For instance, the architect sought feedback on constructability from subcontractors before the bidding proposal phase. Since the design was kept fluid until the end of the project, carpenters in the field were participating in completing the design.
Lack of slack. While all architectural projects suffer severe penalties if they overrun the budget and schedule, Gehry’s projects had reduced slack after adopting Catia. Lacking in-house Catia skills, they had to pay top money to get consultants from the aerospace industry. Most of their contractors could not afford the licensing fee for installing the software. Such is the liability of newness (Stinchcombe 1965)!

Gehry’s projects are also interactively complex because it is extremely hard to anticipate all the ways in which the different technical and social components are going to interact. Unlike standard building projects, Gehry’s buildings involve a variety of non-traditional construction materials which increase unanticipated interactions. For instance, the use of titanium on the Guggenheim Museum in Bilbao was influenced by the favorable prices from dissolution of the former Soviet Union. Another example concerns the metal ribs on the Peter B. Lewis Building: the cold temperature in Cleveland affected the metal ribs near the roof of the building differently than the ones near the ground. As a result, the tolerances varied for different levels of the building. Vincent DeSimone, president of the structural engineering contractor, DeSimone Consulting Engineers, PLLC, was quick to point out that such failure, if left un-addressed, could propagate to adjacent concrete parts, causing systemic damage to the building (interview with DeSimone, February 8, 2003, p. 22).

Replacing traditional 2D drawings with 3D representations created unanticipated interactions among actors who normally don’t interact. Unable to comprehend the Catia model on his own, the chief operating officer of the drywall subcontractor, GQ Contracting Co., spent 17 weeks in Gehry’s office working with a Catia expert: during his past 20 years working in the industry, he had spent less than 8 hours in architects’ offices!

In spite of the increased complexity and tight coupling, Gehry’s firm has successfully built daring buildings since they first used Catia to construct the fish sculpture for the 1992 Barcelona Olympics. They have repeatedly transformed traditional architectural projects into HROs capable of reliability-seeking behaviors. The Lewis Building was completed with all desired functionality only 2 months after the schedule (which is not bad compared to the 3 year planned duration) and within the planned budget. This transformation is enabled by the creative use of IT artifacts, and all the actors we interviewed pointed out that the complex forms on the Lewis Building could only be constructed with the aid of Catia.

In the following section, we will take a closer look at how Catia, in combination with other social/technical elements, contributes to the five cognitive processes that create and maintain collective mindfulness.

**Preoccupation with Failure: Opportunities vs Threats**

In order to achieve mindfulness, actors in HROs display a chronic worry over failures or potential surprises (Weick et al. 1999): The crew members of the nuclear submarine studied by Bierly and Spender (1995) were constantly wary about an encounter with a Russian submarine or a reactor accident and there was widespread recognition at Diablo Canyon that the technology was capable of surprise (Schulman 1993). Likewise, everyone we interviewed admitted that they had apprehensions about the risks of constructing the complex architectural design before and during the project. All the way through the construction, they were “waiting for the disaster to happen” (interview, worker for Spark Steel Erectors & Welding Service, Ltd., April 17, 2003, p. 12).

Prior research indicates that worries about failure can impact actors’ behavior positively to reduce systemic risks in HROs: bringing more attentiveness to all risk factors, treating near misses seriously, or being more likely to report errors (Weick et al. 1999). Our data yield similar findings. With the sword of Damocles hanging over them, the subcontractors took special caution in what they did. Their performance became performativity (Foucault 1977), an awareness of always being subject to risk, on stage in what they do and how they do it. For example, the concrete subcontractor, Donley’s, Inc., double-checked the information in the Catia extractions before starting the field installation, and the workers putting up the drywall had to think really “hard” how to meet the challenge (interview with Ed Sellars, COO, of drywall subcontractor, GQ, September 18, 2002, p. 14).

With time, actors were transformed into subjects of a risk identity, who secure their sense of meaning and reality through their engagement with risk. For instance, since the design was evolving until the end of the project, carpenters were forced to fill in the details to complete the design and had to address design issues for combating performance risk. Gradually, subcontractors found themselves analyzing design aspects more than usual compared to their standard projects by different architects.

However, preoccupation with failure is inherently paradoxical. Consistent with prospect theory (Kahneman and Tversky 1979), the knowledge of the presence of risk alters actors’ behaviors either positively or negatively. Actors with higher aspiration levels may be more challenged, engaging in creative self-representation in the face of risk, while others with lower aspiration levels may be more cautious or feel stressful under risks. Catia helped the architect to actively maintain an appropriate level of risk awareness.
among actors because it could be used selectively to make information more visible for those with higher aspiration levels, and less visible for those unfamiliar with 3D technologies.

In the early stages of the project, rough physical models were used to open the eyes of the client and subcontractors to the complexity of the undertaking.

*When we show them to a client, they get pretty nervous. They are called Schreck models. It’s a Yiddish expression, making people nervous.* (Frank Gehry, Managing as Design Workshop, June 14, 2002, p. 3.)

Although the structural and stress test function of the Catia model showed that the complex geometries were buildable and thereby injected certain predictability into the construction process, making risk information too explicit could backfire. Therefore, Gehry’s office carefully controlled the access to the Catia information. For instance, while they provided full Catia models to the 3D-experienced steel fabricator A. Zahner Company, Gehry’s office only provided 2D blueprints to some other contractors as required by standard construction practice, fearing that the Catia model would induce an exaggerated perception of risk.

**Reluctance to Simplify Interpretations: Diversity vs Common Understanding**

HROs are reluctant to simplify interpretations of the current situation and actively seek out divergent worldviews or perspectives (Weick et al. 1999). As a result, HROs display a negotiated complexity where a “wide range of informal inter-organizational agreements” are constantly negotiated and renewed (Schulman 1993, p. 362).

Unlike traditional projects where the architect can have little direct contact with subcontractors, Gehry Partners seeks expert opinions from subcontractors through an innovative “design-assist” relationship in which subcontractors are invited early on to comment about the design in a consulting capacity before any bids are sought (Tombesi 2002). Getting experts who are ultimately responsible for building the design involved early on helps the architect and engineer to leverage specialty-contractor knowledge (Gil et al. 2001). Pushing the engineering decisions earlier into the design phase was critical for the Lewis Building, because its complex geometries made constructability and economic risks more systemic than traditional buildings. A dramatic example of this comes from A. Zahner Company, the sheet metal fabricator. Early on, Gehry’s office designed the exterior metal of the Lewis Building and their Catia model indicated that the roof and sloping walls would be built in three layers: a wooden deck, covered by a waterproof layer, to which overlapped sheets of metal would be attached. During the design assist, Zahner counter-proposed a more cost-efficient method using metal studs, a thin, non-waterproof metal deck, and a metal shingle they had invented for this application. The shingle they invented had interlocking gutters under each one, and formed a waterproof surface when fitted together. Using metal for the deck was not only less expensive but also mitigated the fire risk associated with the original wood design.

Moreover, Catia helps actors in avoiding over-simplified interpretations in at least two ways. First, its capability to run simulations or consistency tests on the model provides an alternative perspective that a human mind may be incapable of reaching. The concrete subcontractor Donley described how flabbergasted the general contractor was when the Catia model indicated a collision of the concrete with the drywall.

*When they pulled it [the Catia model] up and turned on the drywall layer and the concrete layer, instead of just the drywall layer, the two ran into each other. So it was something that they never saw because they never had those two layers turned on.* (Interview with concrete subcontractor, Donley’s, March 20, 2003, p. 18; emphasis added.)

Second, while the ability of Catia to interface with a constellation of different software accommodates actors skilled in the different phases of computing, its ability to generate 2D drawings compensated for actors with limited ability to see a 2D representation as a 3D object. Vince Mariani, president of Mariani Metal Fabricators, said, “You either have it [3D vision] or you don’t have it” (interview with Vince Mariani, p. 9). As a result, a greater degree of requisite variety in interpretations was promoted.

Paradoxically, the greater variety of inputs also incurs the cost of a lack of consensus and increased conflicts. HRO researchers recommend that organizations institutionalize disagreement management and cultivate credibility and deference (Bierly and Spender 1995; Weick and Roberts 1993). On Gehry’s projects, communications protocols were clearly defined in the contract. Whenever there was a problem or question in the field, the workers would refer to the latest version of the Catia model as “the arbitrator” (interview with Donley, March 20, 2003, p. 8).
To compound the paradox, Gehry was fully aware that digital images cannot represent the feeling of a three dimensional structure, or the subtlety of how elements of the building fit together on a physical site, so he follows a “no computer” policy in his own design work.

Yeah, and Frank always says, he hates to look at the computer because he says it sucks the life out of the form and the computer image, for one thing, is a 2D image. The visualization is very poor, there’s no light, there’s no life to it, it’s dead, it’s just dead and it’s really, and so Frank, yeah, you have to drag him to the computer to get him to look at it. He hates it. (Interview with Craig Webb, design architect, Gehry Partners, January 8, 2003, p. 8.)

Gehry trusted his own creative eyes rather than the power of computing eyes. To minimize the discrepancy between the Catia model and the emotional intent of Frank Gehry’s initial sketches, physical models made by human hands took precedence over digital models in the design process. As the design architect pointed out, “I only trust the physical model. I don’t trust the computer model” (interview with Craig Webb, Gehry Partners, January 8, 2003, p. 8). Like other HROs, trust is maintained to counter-balance the multiplicity of interpretations and skepticism (Weick et al. 1999).

The unwillingness to simplify interpretations increases requisite variety. However, such “divergence in analytical perspectives” (Schulman 1993) may lead to a lack of common understanding. Information technology, in combination with other organization innovations such as design-assist and communication protocols, helps to reconcile this paradox by promoting both diversity and consensus.

**Sensitivity to Operations: Parts vs Whole**

Sensitivity to operations refers to the collective cognitive process where actors comprehend the meaning of the moment while maintaining an integrated image of the overall situation (Vogus and Welbourne 2003; Weick et al. 1999). The requirement of maintaining such situational awareness (Endsley 1997, p. 97) could be paradoxical due to human bounded rationality. Bounded rationality leads actors to focus on parts of the system and to not realize that an improvement on one section of the system may be detrimental to the whole system (Churchman 1968), but at the same time, attention to the whole makes it difficult to zoom in on the finer details of the subsystems.

With its central database and an information threading Website, Catia allowed for measuring and tracking each component of the building. This fine-grain information provided an effective means of risk mitigation (Grabowski and Roberts 1999) by introducing certainty and trust into the environment. Actors were able to make contracts on what they could see and what could be measured.

*Catia is just marvelous. Because when you do a quantity contract, you can track quantities precisely and you can treat everybody fairly. Now if you find you had to add three more pieces, you have absolute precision about what you added, how much, what his unit prices are, this is how much he gets paid….his is basically a quantity survey system.* (Interview with Jim Glymph, partner, Gehry Partners, November 9, 2002, p. 8.)

However, Catia also attends to the other horn of the paradox by showing how elements at one location have “significant time-space distanciated effects” elsewhere (Law and Urry 2003) and how they impact the system as a whole. Since all representations of each component of the building are integrated in the Catia model, every change in one section or component can be used to propagate all necessary changes to related sections of the building plans (Greco 2001). For instance, whenever a change was made to the physical model of the Lewis building, Gehry’s office would digitize it and feed it back into the 3D Catia model. Then a series of algorithm-based structural and stress tests were run to see how the changed parts interacted with other sectors of the building. Sweeping many possible interactions among different parts of the system into the model, Catia helped local actors to make decisions which were more rational on the whole system level.

Another excellent example of how Catia has enhanced actors’ sensitivity to operation is the way it generates 3D <xyz> coordinates for the building. In traditional buildings with the prevalence of rectangular shapes, the architect only generates highly symbolic 2D drawings with limited details. During the construction phase, each subcontractor will identify a few reference points on-site which are based upon the 2D drawings and start to locate walls, plumbing, and so on from these known points. Each measurement is taken off of the last measurement *within* the local 2D plane. By contrast, in Catia, the measurement process is shifted from a 2D grid method to a 3D <xyz> coordinate system. Each measurement is located against a *single* starting point (x = 0, y = 0, z = 0) pre-established before the construction starts. Guided by Catia-generated coordinates, surveyors on the Lewis Building used laser sights, fixed points on the ground, and reflective prisms mounted on nearby building to precisely locate every
element of the building in three-dimensional space. Unlike the traditional 2D grid method using the local information in a given 2D plane, each coordinate in the 3D system contains spatial information relative to the context of the whole building. Therefore, in laying the curving brick wall on the Lewis Building in reference to the control points, a mason was making sure that each brick he laid was at the precise location both relative to his immediate environment and relative to the building as a whole. He was attending to the local and the global simultaneously, without really thinking about the global.

**Commitment to Resilience/Underspecification of Structures: Centralization vs Decentralization**

Commitment to resilience refers to the ability to bounce back from errors and cope with “surprises in the moment” after dangers have become manifest via constrained improvisation (Bigley and Roberts 2001; Weick et al. 1999). Underspecification of structures refers to organized anarchy where fluid decision making is made possible (Weick et al. 1999). We discuss the last two cognitive processes together because they are closely intertwined, as improvisations are often enabled by decoupling decision making from the organization hierarchy and pushing it to actors with domain expertise and experience in local conditions. Moreover, since improvisations in HROs are constrained and anarchy is organized, both processes require a dialectical balance between centralization and decentralization.

On Gehry’s projects, actors in the field were encouraged to come up with innovative ways of building with the aid of information technology. The foreman of the drywall contractor found himself for the first time in his career needing a laptop for checking 2D AutoCAD drawings on the site. Simple new tools were invented: a laser clam and other simple hand tools to provide more accuracy, and tube scaffolding to access hard-to-get-to areas (interview with Ed Sellers, COO, drywall subcontractor, GQ, November 11, 2002, p. 15). The concrete subcontractor, Donley’s, Inc., commented on their strategy to pour the 80 foot high, steeply leaning columns, which were very difficult to form and pour in place and posed a large systemic risk—a crew of 175 veteran construction workers and engineers had to be assigned to do the work.

> I don’t think Donley’s ever put a project engineer on site with 3D AutoCAD. [For] every column that they to pour, they need to plot, you know, in a computer and then slice it at different elevations and then talk back and forth with the engineers, you know, almost once or twice an hour depending on where they were on the job and get them information. You’re constantly radioing information back and forth. (Interview with concrete subcontractor, Donley’s, Inc., March 20, 2003, p. 15.)

With an ad hoc group established outside the traditional operational boundaries to provide expert problem solving, the emerging crisis was contained. Note that the simulation and analytical capability found in Catia and 3D AutoCAD was also enrolled into such informal epistemic networks (Rochlin 1993) to help better diagnose problems.

At the same time, information technology such as Catia helped in balancing the decentralization in the field with centralized control. The architect designated the Catia wire-frame diagram as the controlling document defining the center of structural beams and how shapes interacted with each other. The parametric model extended the architect’s control throughout the whole process of construction by representing all the pieces in a single, integrated image and linked the actors back to the architect. The parametric information embedded in the Catia model was fed into the fabricators’ CNC (Computer Numerical Control) machines, ensuring that the plywood panels were laser-cut to reflect the exact shapes developed by the hands of the architect. In case of a dispute on the construction site, the two Catia stations were the arbitrators (interview with concrete contractor, Donley’s, Inc., March 20, 2003, p. 8). Furthermore, the control of the wire-frame model was clearly defined in the contract: while any change orders should go through the general contractor but copy Gehry’s office, Gehry’s office had to approve any change made to the Catia wire-frame model.

Therefore, both commitment to resilience and under-specification of structures simultaneously require centralization and decentralization. Information technology, in combination with other organizing mechanisms such as contract, communication protocols, and role definitions attend to the two horns of the paradox by empowering local actors to improvise in the face of emerging risks and centrally maintaining certain strategic structures and processes.

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1Weick et al. (1999) identify three ways to establish “commitment to resilience”: improvisation, informal epistemic networks, and ambivalence toward the applicability of past experience. We believe that ability to create informal epistemic networks is a form of improvisation, and a suspicion of past experience falls under the second cognitive process: reluctance to simplify interpretations.
Discussion and Conclusion

The findings of this study suggest organizations rely upon HRO organizing mechanisms to control and mitigate risk in complex socio-technical systems. IT artifacts, in combination with other socio-technical actors, such as competent workers, contracts, and communication protocols, enable collective mindfulness.

This study has two major limitations. First, this study inherits the methodological limitations of a case study design. Second, the retrospective nature of interviews could suffer from faulty memory and a tendency for self-representation. Future research could employ multiple sites to improve the generalizability and a longitudinal design to examine how the five processes of mindfulness change and dynamically play off each other over time. Nevertheless, this study contributes to existing literature on HROs and software risk management in several ways.

Theories of High Reliability Organizations (HROs)

This study complements the existing literature on high reliability organizations in several ways. First, even though information technology has become a pervasive aspect of organizations, current HRO research doesn’t address the issue of IT artifacts except for a few fleeting mentions (e.g., Grabowski and Roberts 1999). This study opens the black box of IT artifacts and looks at the paradoxical role of IT in risk control and mitigation in complex systems. Second, if they do mention information technology (e.g., Weick et al. 1999), HRO research tends to focus on how information technology increases complexity and tight coupling of complex systems. This study also looks at how IT artifacts enable HRO organizing mechanisms, especially mindfulness. Third, while HRO research mostly focuses on a single organization, this study provides an interesting case in an interorganizational setting. HRO theorists posit that a culture based on a homogenous set of assumptions and decision premises is critical for achieving high reliability (Weick 1987). However, it could be difficult to create such a strong single culture when actors come from different organizations with heterogeneous backgrounds. Our case study suggests that a tactical use of IT artifacts as boundary objects (Star and Griesemer 1989) can facilitate meaning making among heterogamous actors (Boland and Tenkasi 1995), and enable high reliability behaviors. Fourth, consistent with the recent development in HRO research arguing for a need to relate HROs to main-stream organizations (Vogus and Welbourne 2003; Waller and Roberts 2003), our case provides an example of how organizations in a tradition-bound industry achieve exceptional accomplishment by becoming reliability-seeking.

Theories of Software Risk Management

Our study also has several implications for large-scale software development. First, going beyond the predominant quantitative, linear causal model of software risk management, this study provides a qualitative description of how systemic risks are controlled and mitigated in complex systems. Second, our study echoes prior research (Moynihan 1997) in that a single, all-encompassing risk taxonomy for all software projects is neither realistic nor practical. Each complex system has its own unique risks and emergent systemic risks are impossible to pinpoint. Risk management is about “attention shaping and intervention” (Lyytinen et al. 1998), and actors must tactically create and maintain mindfulness. Third, current software risk research doesn’t pay much attention to the role of information technology itself in managing the development process. Our study suggests that strategic use of IT artifacts (e.g., centralized database, digital contract) is important in controlling and mitigating risk. Finally, this study contributes to the current debate over the strategic importance of information technology. Contrary to the commodity view (Carr 2003), a tactical deployment of information technology encourages risk taking and contributes to a firm’s competitive advantage: IT does matter and has a strong impact for achieving positive results.

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