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Systemic Risk, IT 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 viewsâ ¦ 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 with divergent perspectives and thus become systemic. The traditional simple 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 Frank Gehry and his firm Gehry Partners, LLC. Gehry and his partners used the 3D representation software Catia tactfully in order 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/mitigation in complex socio-technical systems. IT artifacts such as Catia, in combination with other social/technical actors such as skilled workers, contracts and communication protocols, can enable the five cognitive processes underlying collective mindfulness: preoccupation with failure, reluctance to simplify interpretations (multiple perspectives), sensitivity to operations (seeing the big picture of operation in the moment), commitment to resilience (ability to bounce back from errors and cope with surprises via improvisation), and underspecfication of structures (organized anarchy via fluid decision-making).

Keywords: Risk, High reliability organizations (HROs), Distributed socio-technical systems, systemic risk, Collective mindfulness

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Systemic Risk, IT Artifacts, and High Reliability Organizations: A Case of Constructing a Radical Architecture

Introduction

While 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 are increasingly originated 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 & Roberts, 1993; Weick, Sutcliffe, & Obstfeld, 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 actors****, enable HRO organizing mechanisms such as collective mindfulness.*

Our argument emanates from a detailed examination of how risks are controlled/mitigated in a highly complex architectural project by Frank Gehry and his firm Gehry Partners, L.L.C.. Gehry and his partners used the 3D representation software Catia tactfully 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 embodies an accomplishment of a complex and distributed socio-technical system. Numerous risks could be faced such as those concerning building constructability, liabilities, and vendor management. It's an even riskier endeavor, if the goal is to design and construct a radically new type of building with dauntingly complex geometric surfaces with the help of new technology. The insights we gained from such exercise provide a basis for theorizing about systemic risks in complex socio-technical systems mediated by IT artifacts. This paper contributes to understanding of IS software risk management since constructing a building is not much different from developing a complex software system. In fact, architecture serves as a better metaphor than economics for the information systems design (Boland, 1979, p.268).

Theoretical Framework

Prior Research on IT Risks

The current IS research on risk control strategies concentrates on software development projects (Barki & Rivard, 1993; Barki, Rivard, & Talbot, 2001; Drummond, 1996; Heng, Tan, & Wei, 2003; Keil, 1995; Keil & Robey, 1999; Lyytinen, Mathiassen, & Ropponen, 1996; Ropponen & Lyytinen, 2000; Schmidt, Lyytinen, Keil, & Cule, 2001; Sumner, 2000) and most of them 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 monolithic view of risk, usually that of experts such as the project leaders (Barki et al., 2001) or IS auditors (Keil & Robey, 1999), gets elevated and reified. For instance, though 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 risk and create risk control/mitigation strategies (Williams, Walker, & Dorofee, 1997).

A review of literature also indicates the following: First, almost all IS research emphasizes the adverse effects of risk, though 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 the project within a single organization while considering external stakeholders as environmental factors (Alter & Ginzberg, 1978; Boehm, 1991; Drummond, 1996; McFarlan, 1981; Ropponen & Lyytinen, 2000; Sumner, 2000). Though the stream of research on IT outsourcing takes sometimes an industrial/ecological perspective, their main focus is on make-or-buy decisions(Gopal, Sivaramakrishnan, Krishnan, & Mukhopadhyay, 2003; Jurison, 1995; Lacity & Willcocks, 1998), and dyadic relationships between the organization and the software vendors. However, as IT becomes an increasingly infrastructural technology (Carr, 2003) and is intimately intertwined with an organization's operations, the relationship between IT and risk gets more complicated. As Clemons (1995) indicated, IT enabled re-engineering changes the risk profiles of firms undergoing the organizational change. For example, the competency-destroying re-engineering initiatives increase political risks. Therefore, IS risk researchers need to look beyond the functional project level risks and carefully explain how risks emerge and are contained in larger socio-technical networks where the information systems become embedded.

The current IS risk paradigm of an individual decision maker and the simple causal model of risk is inadequate for understanding risk control/mitigation in complex socio-technical systems. Since such systems are characterized by "interactive complexity" and "tight coupling" (Perrow, 1984), risks increasingly become systemic. 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 the domino effect triggered from a sudden unexpected event (Kaufman & 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 ten risks identified by periodical risk review meetings based on group consensus (Williams et al., 1997).

Prior Research on High Reliability Organizations (HROs)

A complementary stream of research that focuses on risk control in complex socio-technical systems are theories of high reliability organizations (HROs) (Bigley & Roberts, 2001; Roberts, 1990; Waller & 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, consequently suffering from systemic risks. However, they are capable of producing "collective outcomes of a certain minimum quality repeatedly" (Hannan & Freeman, 1984) even in fluctuating and unpredictable work conditions (Weick et al., 1999). Until recently several researchers (Grabowski & Roberts, 1999; Ramanujam & Goodman, 2003; Vogus & Welbourne, 2003; Waller & Roberts, 2003) have pointed out the significance of HROs for main-stream organizations. Weick and et al. (1999)

calls HROs “harbingers of adaptive organizational forms for an increasingly complex environment” (p. 82). With IT-enabled global alliances, rapidly decreasing product life cycle and disruptive innovations, organizations find themselves having to make decisions under tremendous time pressure and with limited information and 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 & Welbourne, 2003).

In order to sustain the complex socio-technical system in face of systemic risks, we posit that organizations rely upon organizing mechanisms characteristic of HROs. However, few HRO research to date has provided substantial empirical evidence on how high-reliability principles could apply to mainstream organizations, except Vogus’ and et al.’s (2003) study of IPO software companies. Studying radical architectural projects can carry Vogus’ and his colleagues’ effort further. Less “exotic” and less “far out” (Scott, 1994) than software companies with a homogenous 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 & Welbourne, 2003).

Concept of Mindfulness

To sustain a complex socio-technical system in face of emerging systemic risks, Weick and his colleagues (Weick & Roberts, 1993; Weick et al., 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 (multiple perspectives), sensitivity to operations (seeing the big picture of operation in the moment), commitment to resilience (ability to bounce back from errors and cope with unexpected events via improvisation), and underspecfication of structures (organized anarchy via fluid decision-making). 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).

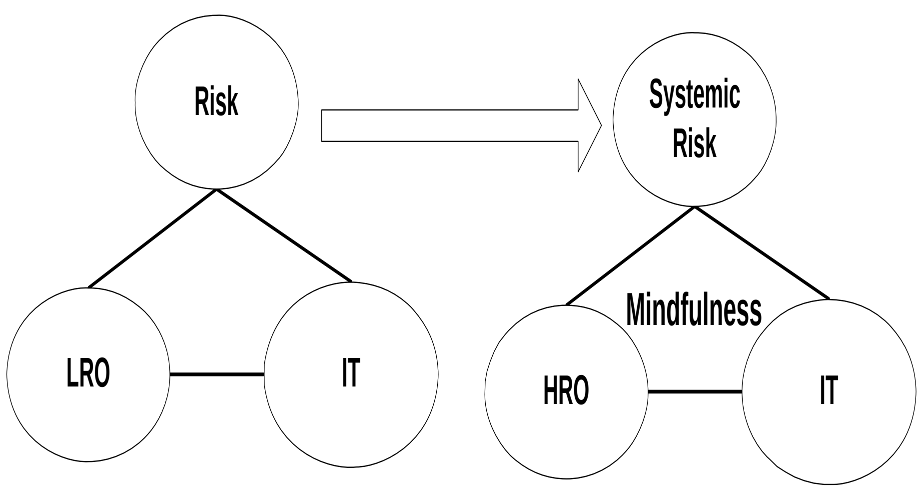

Figure1. Research model (LRO: low reliability organization, HRO: high reliability organization)

However, risk control in HROs is inherently paradoxical: managing interdependence requires extreme hierarchy while coping with environmental uncertainty requires pushing decision-making to the lower level (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 “Pushmepullyou 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 & 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 with its ability to bridge time and space it also helps in loosening up tight-coupling.

Therefore, the purpose of this paper is to exam *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 actors, contribute to enabling one critical HRO mechanism: mindfulness* (Weick & 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 Lewis Building at Case Western Reserve University developed by Gehry Partners, LLC. For the purpose of generalization, we are also following several other ongoing Gehry projects: MIT, Bard and Princeton. Our analysis necessarily refers to some of Gehry’s prior projects. 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 are perfect natural settings for studying risk control in complex systems. First, Mr. 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 technology, 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. While Frank Gehry’s firm is always at the cutting-edge, many of the contractors are from the tradition-entrenched construction industry. This gives us a unique case for connecting mainstream organizations with the “exotic” (Scott, 1994) HROs. Third, Frank 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 exam the role of information technology in sustaining a complex network that accomplishes high-risk tasks.

Catia. Instead of traditional 2D drawings, Gehry’s office used Catia, 3D representation software originally developed in the aerospace industry, to resolve and build the complex surface geometries. Technical features of Catia include: full visualization; simulation (structural/stress test); digital pre-assembly (digital integration of components); communication and coordination (between different actors) (Baba & Nobeoka, 1998) .

Method

Data collected include interviews, documentations, 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, 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 predominate theme in our interviews and 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/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" (Weick & Roberts, 1993; Weick et al., 1999). Therefore, the five cognitive processes underlying "mindfulness" 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 tha*t in order to successfully control/mitigate risk in complex systems requires, organizations rely upon organizing mechanisms characteristic of HROs* (summarized in table 1), and IT artifacts such as Catia, in combination with other social/technical actors, enable the five cognitive processes underlying collective mindfulness (summarized in table 2).

Radical Architectural Projects as High-reliability Organizations (HROs)

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: historically construction demands are fairly stable and there are easy substitutions for both the standardized materials and skilled builders. Architects, clients and contractors conduct business transactions according to industrial practices, contract and tradition and there is very little need for the actors to meet or discuss details of the project. Though 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-boxed process with little vertical integration across different phases. As a result, the 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. ….
>
> (Gerhard Mayer, 9/20/02, p.11)

In fact, the construction industry is considered the most fragmented industry in the world. In the end, following books and norms, traditional architectural projects can achieve great efficiency without worrying about reliability: Reliability takes care of itself.

Traditional Architectural Project *(Low reliability Organization)*	**Gehry's Project** *(High reliability Organization)*
Simple task	Interactive complex task
Standardization	Non-standardization
Black-box	Tight-coupling
Stable environment	Dynamic environment
Efficiency	Reliability

Table 1. Traditional project vs. Gehry's project

By contrast, in Frank Gehry's projects, reliability can no longer be black-boxed. Instead, reliability was a mindful achievement of a carefully knitted socio-technical system that exhibits HRO characteristics. These projects are tightly-coupled in both organization-environment relations (Vogus & Welbourne, 2003) and within the socio-technical system itself (Perrow, 1984) according to the criteria identified by HRO scholars (Perrow, 1984; Roberts, 1990; Vogus & 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 (Thompson, 1967), the next phase using the prior phase's outputs as its own inputs. Due to increased complexity of Ghery's projects, the interactions among different actors are becoming reciprocally interdependent (Thompson, 1967). For instance, the architect sought feedbacks on costructability 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. 3) *lack of slack.* While all architectural projects suffer sever penalty if they overrun the budget and schedule, Gehry's projects suffer extremely limited resources and shrunk slack after adopting Catia. Lack of in-house talent, 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. 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 materials, 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 dissolution of the former Soviet Union. Another example concerns the metal ribs on the 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 got twisted and parts didn't fit. The structural engineering contractor DeSimone was quick to point out that such failure, if left un-addressed, could also propagate to adjacent concrete parts, causing systemic damage to the building. Therefore, unlike traditional projects, Gehry's projects increasingly suffer from systemic risks.

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 spent 17 weeks in Ghery's office working with the 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 (Vogus & Welbourne, 2003). 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 with only a 2% percentage over the planned budget (which is excellent according to industry standard). This transformation is enabled by the creative use of IT artifacts, as all the actors we interviewed point out that the complex forms on their buildings were only buildable with the aid of Catia.

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

Preoccupation with Failure: Opportunities vs. Threats

In order to achieve mindfulness, actors in HROs have a chronic worry over failures or potential surprises (Weick et al., 1999): While the crew members of the nuclear submarine were constantly wary about an encounter with a Russian submarine or a reactor accident (Bierly III & Spender, 1995), 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" (Spark Steel, 4/17/03. 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 more likely to report errors (Weick et al., 1999). Our data yields 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 under risk, on stage in what they do and how they do it. While the concrete subcontractor Donely 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 (Ed Sellars, 9/18/02, 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 a lot more than usual for even the standard design of structural elements on other jobs by different architects.

However, preoccupation with failure is inherently paradoxical. Consistent with prospect theory (Kahneman & 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-representations in the face of the 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 make risk information more explicit as well as hide risk information.

In the early stage of the project, scary physical models and ugly 3D 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, 6/14/02, p. 3)

While the structural/stress test function of the Catia model showed that the complex geometries were buildable and injected certain predictability into the construction process, making risk information explicit could backfire. Therefore, Gehry's office religiously controlled the access to the Catia information. While providing 3D savvy Steel fabricator Zahner full Catia models, Gehry's office denied the dry wall subcontractor GQ such access during the bidding process, fearing that the Catia model would induce an exaggerated perception of risk thereby inflating their bidding price. Other features of Catia that Gehry's office drew upon include: password protected FPT site archiving Catia files on the Bard project, the multiple layers and embedded information in Catia models being selectively reconfigured for intended subcontractors. Information hiding is a common risk control strategy (Lyytinen, Mathiassen, & Ropponen, 1998) and IT makes it easy.

Therefore, preoccupation with risk has opposite effects on different actors with different aspiration levels. Information technology enables actors to have an appropriate level of worry about risk, because it can manipulate the amount of risk information to be communicated.

Reluctance to Simplify Interpretations: Diversity vs. Common Understanding

HROs are reluctant to simplify interpretations of the current situation by actively seeking out divergent worldviews or perspectives among members of organization (Weick et al., 1999). Instead, the reality in HROs is 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 almost has no direct contact with subcontractors, Gehry Partners seek expert opinions from subcontractors through the innovative "design-assist", where subcontractors are invited to comment early on about the design in an engineering capacity before the bid is awarded (Tombesi, 2002). Getting people who are ultimately responsible for building the design involved early on helps the architect/engineer to leverage specialty-contractor knowledge including: 1) subcontractors' intimate knowledge about space needs during construction (e.g. access path for bringing equipment and materials, routing clearances for workers moving around)(Gil, Tommelein, Kirkendall, & Ballard, 2001), 2) knowledge gained from "cross-fertilization", where subcontractors piggyback on prior experiences with other projects by different owners and different design firms (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 metal curtain wall for the exterior of the Lewis Building and the Catia model indicated that this could be built with simple metal studs in the field. During the design assist, based on their experience on a prior Gehry project and the parametric information in the Catia model, Zahner counter-proposed a more cost-efficient prefabricated shingle configuration. This also led to another innovative idea:

using metal for the deck on top of the structural steel on the building, which was not only less expensive but also subsequently mitigated the fire risk associated with the original wood design.

Moreover, Catia helps actors in avoiding over-simplified interpretations in at least two ways. Firstly, its capability to run millions of simulations or structural/stress tests within seconds, thus providing 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* [italics added] because they never had those two layers turned on…"
>
> (Donley, 3/20/03, p.18)

Secondly, 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 poor 3D visions, an innate character. In the steel subcontractor Mariani's words, "you either have it [3D vision] or you don't have it' (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. HROs researchers recommend that organizations institutionalize disagreement management and cultivate credibility and deference (Bierly III & Spender, 1995; Weick & Roberts, 1993). On Gehry's projects, communications protocol was 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" (Donley, 3/20/03, p.8). To avoid the discrepancy between the Catia model and Frank Gehry's gestural model which captured the architect's original intents, Gehry stuck to a "no computer" policy.

> 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.
>
> (Craig Webb, 1/8/03, p.8)

Whenever the original intents were concerned, physical models made by human hands took precedence over digital models. Like other HROs, trust is maintained to counter-balance the redundancy that takes the form of diversity and skepticism (Weick et al., 1999).

Therefore, 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 big picture of the overall situation (Vogus & Welbourne, 2003; Weick et al., 1999). The requirement of maintaining such "situational awareness" (Endsley, 1997, p. 97) could be paradoxical due to human being's bounded rationality. While human actors tend to focus on parts of the system and not realize that an improvement on one section of the system may be detrimental to the whole system (Churchman, 1968), an attention to the whole makes it difficult to zoom in on the finer details of the sub-systems.

With its central database and a information threading Website, Catia allowed measuring and tracking each components of the building. The "fine-grain information" is a effective means of risk mitigation (Grabowski & Roberts, 1999) by introducing certainty and trust into the environment. Actors were able to make a contract on what they could see and what could be measured (Jim Glymph, 11/9/02, p.8).

> "… 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. …This is basically a quantity survey system."
>
> (Jim Glymph, 11/9/02, p.8)

However, Catia also attends to the other horn of the paradox by showing how elements at one local location have "significant time-space distanciated effects" elsewhere (Law & 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 digitalized it and fed it back into the 3D Catia model. Then a series of algorithm-based structural/stress tests were ran to see how the changed parts interact with other sectors of the building. "Sweeping"(Churchman, 1968) 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 elements 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 the spatial information relative to the context of the whole building. Therefore, in laying the curvy brick wall on the Lewis Building in reference to the control points, a carpenter 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.

Therefore, maintaining a sensitivity to operations requires actors to attend both to the meaning of the moment and the big picture of the whole system. Information technology attends to both horns of the paradox by providing fine-grain details embedded in the global information.

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"[1] (Bigley & Roberts, 2001; Weick et al., 1999). Underspecfication 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 hierarchy and pushing decision-making to actors with expertise and experience. 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 (Ed Seller, 11/11/02, p.15). The concrete subcontractor Donley commented on their strategy to pour the 80 feet high leaning columns in the air, which were so tricky to put up that they would fall over causing systemic risks: One hundred seventy five veteran carpenters had to be assigned to do the work.

> I don't think Donley's ever put a project engineer on site with 3D AutoCad and [for] every column that they to pour, they need to plot, you know, in a computer and then slice it at different elevation 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.
>
> (Donley, 3/20/03, p. 15)

As the ad hoc group was established outside the traditional operational boundaries to provide expert problem solving, the emerging crisis was contained. Note 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 diagram as the controlling document defining where the controlling structural lines were and how shapes interacted with each other. The parametric model extended the architect's control throughout the whole process of construction by bringing all the pieces together and tied the actors back to the architect. The parametric information embedded in the Catia model were fed into the fabricators' CNC 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 arbitrator" (Donley, 3/20/03, 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.

[1] Weick et al. (1999) identifies three ways to establish "commitment to resilience": improvisation, informal "epistemic networks", and ambivalence towards 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 2nd cognitive process: "reluctance to simplify interpretations".

Mindfulness	Paradoxes	Org. Mechanisms	Catia Attributes	Comments
Preoccupation with failure	Opportunity vs. threat		Structural/stress test; Password; Layers; Embedded information;	Make risk vivid; Hide information;
Reluctance to simplify interpretations	Diversity vs. Common Understanding	Design-assist; Gehry sign-off;	Simulations; Layers; Visualization; 2D extracts;	Different actors / visual styles; Alternative perspective;
Sensitivity to operations	Parts vs. Whole		Central database; Simulations;	Global vs. local information; Make explicit interactions among different parts;
Commitment to resilience	Centralization vs. Decentralization	Contract; Comm. Protocol; General surveyor;	Simulations	Correct errors on the fly
Underspecfication of structures			Wire-frame model; xyz measurements;	Control key points while leaving others open

Table 2. IT artifacts contributing to creating and maintaining the five cognitive processes underlying "mindfulness"

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

Discussion and Conclusion

The findings of this study suggest organizations rely upon HRO organizing mechanisms to control/mitigate risk in complex socio-technical systems. IT artifacts, in combination with other socio-technical actors, such as competent workers, contract and communication protocol, enable such mechanisms as 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 tendency of self-representation. Future research could employ multiple sites to improve the generalizability and a longitudinal design to exam how the five processes of mindfulness changes and dynamically play off with 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 prior literature on high reliability organizations (Bigley & Roberts, 2001; Roberts, 1990; Waller & Roberts, 2003) 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 a few fleeting mentions (e,g, Grabowski & Roberts (1999). This study opens the black-box of IT artifacts and looks at the paradoxical role of IT in risk control/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 enables HRO organizing mechanisms, especially mindfulness. Third, while HRO research mostly focuses on a single organization, this study provides an interesting case in an inter-organizational setting. It gives organizational culture, one of the most promising HRO principles (Weick, 1987), a different meaning: it may be inefficient when actors come from heterogeneous backgrounds. Our case study suggests an alternative source of high reliability: the tactful use of IT artifacts. Fourth, consistent with the recent development in HRO research (Vogus & Welbourne, 2003; Waller & Roberts, 2003) arguing for a need to relate HROs to main-stream organizations, our case provides an example of how organizations in a tradition-bound industry achieve exceptional accomplishment by becoming "reliability-seeking"(Vogus & Welbourne, 2003).

Theories of Software Risk Management

Our study also has several implications for large-scale software development. First, going beyond the predominant quantitative, simple casual model of software risk management, this study provides a qualitative description of how systemic risks are controlled/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[2]. Our study suggests that strategic use of IT artifacts (e.g. centralized database, digital contract) is important in controlling/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 advantages: IT does matter and has a strong impact for achieving positive results.

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[2] We thank Hemant Jian for pointing this out.

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