Chapter IV
On the Study of Complexity in Information Systems

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ABSTRACT

This article addresses complexity in information systems. It defines how complexity can be used to inform information systems research, and how some individuals and organizations are using notions of complexity. Some organizations are dealing with technical and physical infrastructure complexity, as well as the application of complexity in specific areas such as supply chain management and network management. Their approaches can be used to address more general organizational issues. The concepts and ideas in this article are relevant to the integration of complexity into information systems research. However, the ideas and concepts in this article are not a litmus test for complexity. We hope only to provide a starting point for information systems researchers to push the boundaries of our understanding of complexity. The article also contains a number of suggested research questions that could be pursued in this area.

INTRODUCTION

This article reflects some thoughts of the editorial review board for the complexity area of this new journal. We are pleased to see a journal introduced whose mission is to truly emphasize a systems approach in the study of information systems and information technology. Within this area of the journal, we will focus on the issue of complexity. We think it is befitting of the area that this article was a group effort. Complexity has many aspects, and we are eager to receive submissions that are truly informed by a systems approach in general and a complexity perspective in particular.

In the sections that follow, we will outline some thoughts on what complexity is, what it can mean when used to inform information systems research, and how some individuals and organizations are using notions of complexity. We provide some comments on how organizations are dealing with technical and physical infrastructure complexity, as well as the application of complexity in specific areas such as supply chain management and network management to more general organizational issues. We offer these pages as a beginning of a dialog on the topic, not as an exhaustive or restrictive set of criteria. We believe the concepts and ideas in this article are relevant to the integration of complexity into information systems research and that, in most cases, some aspect of these topics will be apparent in future submissions. However, the ideas and concepts in this article are not a litmus test for complexity. We expect, and hope, that information systems researchers will push the boundaries of our understanding of complexity through their efforts, which they report in this journal.

COMPLEXITY CONSIDERED

Human life is frequently described as becoming more and more complex, and rightly so. It seems that the terms "complex" or "complexity" appear everywhere. In some part, this is because life really is complex! But this conclusion is also driven by the fact that over the last few decades, we have learned more about the nature of complexity and the role that complexity plays in our lives. Complexity is a feature of all living and natural systems. The approach we speak of has permeated the natural sciences as a way of understanding natural order. However, its application to human systems is to date fragmented.

A recent issue of the journal *Complexity* (Complexity at large, 2007) provides a glimpse of this phenomenon. The first seven pages provide an index into complexity studies from a wide range of disciplines. Here we find news about studies in biodiversity, weather prediction, stem cells, learning, gene therapy, battlefield operations, algorithm development, morality, neural activity in primates, topographical issues in anthropology, organ development, consciousness, robotic reasoning, human moods, and, appropriately, complexity measures. Presumably, the common thread in all of the articles referenced is some notion of complexity.

The focus of this area in the *International Journal of Information Technology and the Systems Approach* (IJITSA) cannot, unfortunately, be so broad. We must limit our scope to topics in information technology. That, however, will not be a serious constraint. The application of complexity theory to information system design, implementation, testing, installation, and maintenance is well within the scope of this IJITSA area. Fundamental issues related to definition, measurement, and application of complexity concepts are valid areas of inquiry. In looking at complexity in information technology, however, we cannot overlook the organizational structures that technology supports, in the image of which information technology is designed.

Information technology underlies and supports a huge part of the operations of modern organizations. By extrapolation, therefore, the role of information systems as they support complex organizational processes is well within our scope. Simon (1996) argued that complexity is a necessary feature of organizations and Huber (2004), in a review of management research, underscores the importance of recognizing that organizational decision making in the future will occur in an environment of growing and increasing complexity.

Indeed, information technology underlies a large part of life itself for young people today. Their lives are entwined in online social networks. They may have a "relationship" with hundreds of other people who they have never met. Their identity may be connected to online activities in ways that no other prior generation has ever experienced. Concepts such as "network" and "relationship" are fundamental to complexity. Investigations of information technology supported communities through a complexity theory lens are certainly within the scope of this area of IJITSA. But complexity and interdependency underlie "normal" social science as well. Granovetter's seminal work (1973, 1983) on "weak ties" in social networks remains a model today in social network theory (Watts, 2003). As well, Lansing's study of Balinese farming reflects a complex systems approach to traditional society (Lansing, 2006).

COMPLEXITY EXPLORED AND DESCRIBED

But let us not get ahead of ourselves, for our understanding of complexity is still evolving. A good starting point for this area is to define, to the extent that we can, what our terms mean. A distinction has to be made between a system having many different parts—complexity of detail and a system of dynamic complexity. In the case of complexity of detail, the system may be treated by categorization, classification, ordering, and systemic-algorithmic approach. A system has dynamic complexity when its parts have multiple possible modes of operation, and each part may be connected, according to need, to a different part. Dynamic complexity exists when a certain operation results in a series of local consequences and a totally different series of results in other parts of the system (O'Connor & McDermott, 1997). So we see that even constructing a definition is no small task when dealing with the topic of complexity. In fact, we will not be surprised to publish papers in the future that clarify or expand the definitions we offer today.

Complexity is a characteristic that emerges from the relationship(s) of parts that are combined. The idea that the "whole is greater than the sum of the parts" is fundamental to considerations of complexity. Complex describes situations where the condition of complexity emerges from that being considered. Complexity cannot be foreseen from an examination of the constituent parts of a thing. It is a characteristic that emerges only after the parts are entwined in a way that subsequent separation of the parts would destroy the whole. We can see hints of this characteristic even in descriptions of situations that are not focused specifically on complexity. For example, Buckland (1991) writes of information systems that support libraries: "By complexity, we do not simply mean the amount of technical engineering detail, but rather the diversity of elements and relationships involved" (p. 27). He further observes that systems that are provided on a noncommercial basis are necessarily more complex than commercial systems due to the political dimension of their provision. Clearly, this notion of complexity goes well beyond the hardware and software and considers a much broader system in use.

One widely accepted definition of a complex adaptive system comes from Holland (1995), as cited in Clippinger (1999). A complex adaptive system is said to be comprised of aggregation, nonlinearity, flows, diversity, tagging, internal models, and building blocks. What these mean in the context of information systems is the subject of an entire paper. The basic principle is that complex systems contain many interaction variables that interact together to create emergent outcomes. Initial conditions may be local and small in scale, but may gain nonlinearity due to aggregation, and so forth.

Thinking in terms of complexity and some of the concepts and metaphors that are emerging in the study of complexity is a departure from some traditional scientific thinking. Many approaches to understanding that are "scientific" have involved decomposing some thing into its parts so that the parts may be better understood. This reductionism in understanding often sacrifices as much as it gains by losing the richness of context in which the object studied exists. Such an approach provides great knowledge about parts, but little about the whole. It assumes that each part has its own trajectory unaffected by other parts. Moreover, this approach is limited by relying entirely on countable "units" as opposed to analog conditions.

The dynamics of interaction between elements gives rise to a number of features that are difficult to reconcile with some of the tenets of the "classical" IS paradigm and its methods for dealing with complexity (see Merali, 2004, for more detail). Schneider and Somers (2006) identify three "building blocks" of complexity theory: nonlinear dynamics, chaos theory, and adaptation and evolution. By nonlinear dynamics, they refer to dissipative structures that exhibit an inherent instability. These structures may be easily affected by a small change in the environment. They do not tend toward equilibrium. Rather, they go through transitions, typically moving into conditions of greater complexity both quantitatively and qualitatively. This is fundamentally different from the General Systems Theory inclination toward equilibrium.

Chaos is a deterministic process that is progressively unpredictable over time. Chaos theory provides a basis for the study of patterns that initially seem random, but upon closer inspection turn out to be nonrandom. Schneider and Somers observe that under chaos, a basis of attraction is formed that brings about the nonrandomness. A "strange attractor" accounts for the system's bounded preferences.

Chaos is critical to the process of adaptation and evolution. Schneider and Somers (2006) observe that complex adaptive systems (CAS) reflect an ability to adapt through the emergent characteristic of self-organization. Karakatsios (1990) has developed a simple illustration of how order can emerge from chaos or randomness in such systems. First, a matrix is randomly populated with a binary variable, say zeroes and ones. Let a zero value represent the notion of "off" and a one value represent the notion of "on". Next, the following algorithm is iteratively applied to the matrix:

For each cell in the matrix
If 3 or fewer neighboring cells and this cell are on, set this cell to off.
If 6 or more neighboring cells and this cell are on, set this cell to on.
If 4 neighboring cells are on, turn this cell on.
But if 5 neighboring cells are on, turn this cell off.
Repeat until no changes occur.

Some of us have tried it and found that the matrix typically stabilizes in as few as five or six iterations. However, not all systems have the capacity to adapt. Some systems find small changes in the environment too disruptive to ever evolve to another state. Catastrophe theory studies systems that may transition into one of two states, one stable and the other highly chaotic. Whether a system enters a chaotic state or remains stable may be highly sensitive to initial conditions, so sensitive in fact that it may not be possible to know inputs precisely enough to predict which state the system will enter. This may appear to be troublesome to those attempting to manage organizational systems, but work in the area of complex adaptive systems tells us that systems can adapt and learn and information can be fed back to the control mechanism (management) to keep the organization on a relatively stable path. On the other hand, other systems are too stable and do not react to the environment in any meaningful way. These systems are essentially inert. They continue in their current behavior oblivious to the environment around them. Somewhere between these two extremes are systems that are able to react to the environment in a meaningful way. Kauffman (1995) suggests it is the systems "poised" at the edge of chaos, the ones that are not too stable and not too instable, that have the flexibility to evolve. He theorizes a set of variables that affect the degree of chaos/nonchaos in a system, and hence its ability to evolve. The application of chaos theory to information systems design, implementation, testing, installation, and maintenance is well within the scope of IJITSA.

With the impressive growth of the field of complex systems, the lack of a clear and generally accepted definition of a system's complexity has become a difficulty for many. While complexity is an inherent feature of systems (Frank, 2001), a system may be complex for one observer while not for another. This is not due to subjective observation, but due to the observers' scales of observation. A system that is highly complex on one scale may have low complexity on another scale. For example, the planet Earth is a simple dot—a planet moving along its orbit—as observed on one scale, but its complexity is substantial when viewed in terms of another scale, such as its ecosystem. Thus, complexity cannot be thought of as a single quantity or quality describing a system. It is a property of a system that varies with the scale of observation. Complexity, then, can be defined as the amount of information required to describe a system. In this case, it is a function of scale, and thus a system is to be characterized by a complexity profile (see Bar-Yam, 1997, 2002a, 2002b, 2004).

COMPLEXITY AS A LENS FOR INVESTIGATION

Complexity concepts have been deployed to study complex systems and their dynamics in two ways. The first is through the direct use of complexity concepts and language as sense-making and explanatory devices for complex phenomena in diverse application domains. To capture the "unfolding" of the *emergent* dynamics, we need to have methods that can provide a view of the *dynamics* of the *changing* state in continuous time. The complex systems approach to doing this is by describing state cycles using mathematical models or by running simulations.

The second is through agent-based computational modeling to study the dynamics of complex systems interactions and to reveal emergent structures and patterns of behavior. Agent-based computational modeling has characteristics that are particularly useful for studying socially embedded systems. Typically agent-based models deploy a diversity of agents to represent the constituents of the focal system. The modeler defines the environmental parameters that are of interest as the starting conditions for the particular study. Repeated runs of the model reveal collective states or patterns of behavior as they emerge from the interactions of entities over time. Agent-based models are very well-suited for revealing the dynamics of far-from equilibrium complex systems and have been widely used to study the dynamics of a diversity of social and economic systems.

With the escalation of available computational power, it will be possible to build bigger models. The mathematicians and the natural scientists have a powerful battery of technologies for studying dynamical systems. However, for social systems, the specification of the components for the construction of agent based models is a challenging prospect. The challenge of creating entire mini-economies in silicon is not one of processing power, but one of learning how to build sufficiently realistic agents.

The science of complexity allows us to consider the dynamic properties of systems. It allows us to explore how systems emerge and adapt. When viewed as a complex adaptive system, it provides us a mechanism for dealing with both the technical and the social aspects of systems. We have new metaphors for articulating how IS are used and how they evolve. We move from concepts embedded in an assumption of stable hierarchies to ideas embedded in an assumption of networks of dynamic relationships. With this, we move closer to a unified view of IS and management.

Simon (1996) writes: "Roughly, by a complex system I mean one made up of a large number of parts that have many interactions" (p. 183). This simple definition can be readily applied to organizations and their information systems. Thus, an organization is a complex system if it has many units (departments, for example) and there are many interactions among units. A complex information system is one that has many elements (programs, modules, objects, relationships, attributes, databases, etc.) that interact in many ways.

At the most fundamental level, technological developments have the potential to increase connectivity (between people, applications, and devices), capacity for distributed storage and processing of data, and reach and range of information transmission and rate (speed and volume) of information transmission. The realization of these affordances has given rise to the emergence of new network forms of organization embodying complex, distributed network structures, with processes, information, and expertise shared across organizational and national boundaries. The network form of organizing is thus a signature of the Internet-enabled transformation of economics and society. Merali (2004, 2005) suggests conceptualizing the networked world as a kind of global distributed information system.

Yet, this only begins to get at the complexity of complex systems. Systems have boundaries that separate what is in the system from what is outside—in the environment. Environments themselves may be complex, and the system, the organization, or the information system may interact with the environment in many ways. Moreover the interactions themselves may be complex.

An information system that exists with a particular organization (ignoring inter-organizational systems, for the moment) has the organization as its environment. If the organization and its information requirements are stable, then the information system itself has relatively little need to change, other than to keep up with changes in relevant hardware and software technologies (which may be no mean feat in and of itself).

However, it seems to be the norm today for organizations and their environments to be in a state of constant change. Organizations must adapt to environmental changes in order to survive, not to mention thrive. The same can be said for information systems in organizations. Organizations may even rely upon their information systems in order to understand, analyze, and adapt to such changes. Thus, we say that organizations and information systems are one form of complex adaptive systems, a topic of great interest today among those interested in systems theory.

Simon (1996) describes three time periods in which there were bursts of interest in studying complex systems. The first followed World War I and resulted in the definition of "holism" and an interest in Gestalts, and a rejection of reductionism. The second followed World War II and involved the development of general systems theory, cybernetics, and the study of feedback control mechanisms. In one perspective, in the second era, the information system of an organization is viewed as a feedback mechanism that helps managers guide the enterprise towards its goals.

We are now in a third era. The foundation had been laid for the development of the concept of complex adaptive systems, elements of which include emergence, catastrophe theory, chaos theory, genetic algorithms, and cellular automata. Complex adaptive systems receive sensory information, energy, and other inputs from the environment, process it (perhaps using a schema in the form of an updatable rule-base), output actions that affect the environment, and feedback control information to manage system behavior as learning occurs (update the schema).

Complex adaptive systems are reminiscent of the concepts of organizational learning and knowledge management, which have been viewed from the perspectives of Churchman's (1973) inquiring systems which create knowledge or learn and feed that knowledge back into an organizational knowledge base (Courtney, 2001; Courtney, Croasdell, & Paradice, 1998; Hall & Paradice, 2005; Hall, Paradice, & Courtney, 2003). Mason and Mitroff (1973), who studied under Churchman as he was developing the idea of applying general systems theory to the philosophy of inquiry, introduced this work into the IS literature early on, and it has ultimately had great influence on systems thinking in IS research.

Complexity in this context is in the form of "wicked" problems (Churchman, 1967; Rittel & Weber, 1973). In sharp contrast to the well-formulated but erratically behaving deterministic models found in chaos theory, in a wicked situation, "formulating the problem *is* the problem," as Rittel and Weber put it (1973, p. 157, emphasis theirs). The question that arises here is whether problems in management domains that involve human behavior are of such a different character that elements of complexity theory and chaos may not apply. This is clearly an open question and one that can only be addressed through additional research.

WHAT DOES THIS MEAN FOR IS?

There is no question that information systems in organizations, as they have been defined, are complex. The very basis of information systems, the underlying technologies, programs, machine language, and so forth, are inherently ways of dealing with complexities of calculation and the complexity of the use contexts, in this case, the organization. What has not been included in the description of information systems as "systems" are several key notions from complex adaptive systems and current compute models that directly or indirectly reflect complex systems modeling. These include machine learning, Bayes nets, inferencing algorithms, complex calculations for science applications, visualization, virtualization schemes, network traffic modeling, social networking software, and diverse other areas.

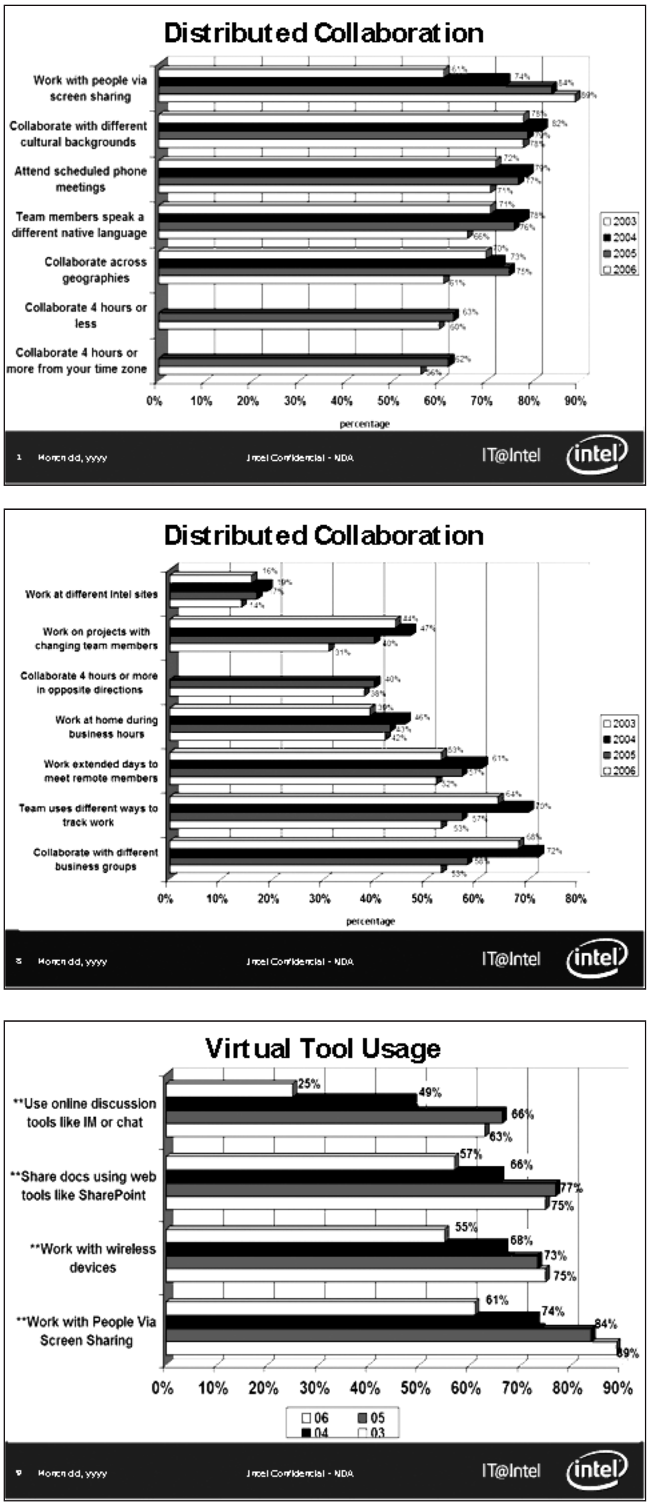
Organizational analysis as we know it, even in its evolution to be inclusive of multiple paradigms of research, has failed to acknowledge that organizations are inherently complex. Organizations defy simplification, and the only way to deal with this fact is to embrace and manage complexity. Structuration theory and actor network theories applied to organizations both begin to cope with this reality that the whole is greater than the sum of the parts and that outcomes are emergent.

While visionary management authors like Wheatley (1992, 2006), Weick and Sutcliffe (2001), Axelrod and Cohen (2000), and others have written directly on the topic, the application of their thinking is not evident in the ordinary management situation. There is some adoption on the edges in areas where complexity is defined by the behavior of objects, like supply chain management, RFID tagging and tracking, and network traffic. However, these applications often occur without recognition of the greater framework they represent. Further, attempts to generalize from these technically specific domains to the overall behavior of the organization have not been accepted easily.

What is missing from the computational paradigms that do use complexity in their mode of operation is simply the recognition that this is so. It is as if connectionists have entered into the world of dealing with complexity as a "natural environment", like air or water, which ceases to be noticed.

At this point in history, the organization and its information systems are inextricable. There is no turning back, as there may have been as late as the 1970s when paper systems were still an option.

Figure 1.


Distributed Collaboration
Work with people via screen sharing
Collaborate with different cultural backgrounds
Attend scheduled phone meetings
Team members speak a different native language
Collaborate across geographies
Collaborate 4 hours or less
Collaborate 4 hours or more from your time zone
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Distributed Collaboration
Work at different Intel sites
Work on projects with changing team members
Collaborate 4 hours or more in opposite directions
Work at home during business hours
Work extended days to meet remote members
Team uses different ways to track work
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Table 1. Some research questions related to complexity and information systems

Does chaos theory really apply to the IS domain? IS seems to have characteristics more resembling those of wicked problems where formulating the problem is the problem. Chaos consists of well-specified models whose behavior gets less predictable over time because of nonlinearities. The two do not seem to be isomorphic.
How does one go about modeling agents in IS problems? Modeling computer systems may not be so difficult, but modeling human actors seems to be problematic. How, for example, do you model changing schemata as learning occurs? Human agents have almost limitless attributes. What characteristics of human agents are important to model? How do you model the exchange of knowledge among agents?
As organizations and IS become more intertwined, it becomes increasingly important that the IS be reliable. Does chaos theory make sense here, in that the organization's behavior may be unpredictable if the IS fails?
How does management's attitude about importing innovation from the environment affect the IS function? Does sharing or importing innovations help the organization fit the environment?
How do we define and measure organizational and information systems complexity? How do we test complex models of organizations and information systems? We need to measure to be able to test.
Is it possible to organize and manage so that the organization and its information systems co-evolve and emerge together? Can prototyping help support co-evolution?
From Rouse (2007, pp. 16-17): What architectures underlie the physical, behavioral, and social phenomena of interest? How are architectures a means to achieve desired system characteristics? How can architectures enable resilient, adaptive, agile, and evolvable systems? How can and should one analytically and empirically evaluate and assess architectures prior to and subsequent to development and deployment? What is the nature of fundamental limits of information, knowledge, model formulation, observability, controllability, scalability, and so on? How can decision support mechanisms be developed for multistakeholder, multi-objective decisions?

Aside from back-ups for legal purposes, all large organizations are fully committed to their information systems environments as infrastructure. Indeed, technical infrastructure encroaches on physical infrastructure with outsourcing, telecommuting, globalization of work, and other major trends. As information systems facilitate more and more networked operations and distributed work, as enterprise applications emerge that serve one and all, the very functioning of the organization, especially a large one, becomes impossible without an information system. Studies of Intel's workforce find that on six dimensions of time, space, organizational affiliation, software tools, culture, and number of projects, the workforce can be said to be operating approximately 2/3 in "virtual mode"—across time, space, culture, multiple teams, and so forth (Wynn & Graves, 2007).

This means that the workforce coordinates itself mostly on the network. If the medium of coordination, action, and work production is primarily a network, it more and more resembles a rapidly changing complex system that has the possibility of being self-organizing in a very positive way. Indeed, that is the case. But without the recognition that virtuality equates with greater capacity for self-organization (and that self-organization is adaptive), then this enormous potential will be not only underutilized, but at times interfered with, sub-optimized, and cut off from its latent functionality.

The interesting thing is that the science is there; the systems are there; the computational capacity is there. All that is lacking is the consciousness to apply them. Some notable exceptions exist, however. The Department of Defense Command Control Research Project has a number of publications that apply a self-organizing system concept to hierarchical command and control systems. Boeing PhantomWorks (Wiebe, Compton, & Garvey, 2006) has drawn out the Command and Control Research Program (CCRP) scheme into a large system dynamic model. In short, there is no lack of research and conceptual material.

But getting this across to people responsible for the stock price and cost containment of a very large organization is no simple matter. It seems risky, even though it is likely much less risky than acting as if the world were a stable place and a linear progress model will provide a safe approach to operations. As a defense strategy organization, CCRP recognizes acutely that they are dealing with volatile, rapidly changing, network-based asymmetrical conflicts that also have great potential for reaching critical mass and nonlinear effects so large they could overwhelm conventional forces, or at least those using conventional methods.

The large organization lives in very much the same world as the military organization, only effects are slower to take hold and direct loss of life is not normally a risk. However, there are environmental instabilities in global politics, competition and licensing, labor forces, currency and liquidity, stock market fluctuations, energy costs, supply chains that reach across the globe, transportation, changing demand, and of course, competitors. All of these elements together, and others not noted, comprise a highly complex and turbulent environment. That is the external environment. The internal environment of the organization and its information system can create the adequate response to the external environment. For that to happen, both workforce and information systems need to be seen as comprising an adaptive resource. This is where explicit recognition of complexity can make the difference.

A recent special issue of the journal *Information Technology & People* (Jacucci, Hanseth, & Lyytinen, 2006) took a first step in applying this approach to what we know about information systems research (Benbya & McElvey, 2006; Kim & Kaplan, 2006; Moser & Law, 2006). However, a journal that is regularly dedicated to this theme is needed both to publish available research and to foster further research on this important topic.

We offer a set of possible research questions in Table 1. This list is by no means exhaustive, and we welcome work on these and others that our audience may conceive.

CONCLUSION

Few would argue that complexity is not inherent in living today. As networked information environments become more integrated into both our social and our working lives, the number of relationships with others may grow, and the relationships we have with them may become more complex. We exist, along with our relationships, in an environment of equal or greater complexity.

We strive to understand what complexity means and what it implies for us. We believe that a better understanding of complexity will give us a better ability to function more effectively and achieve our goals, both personal and professional. We welcome research that will broaden our understanding of complexity, help us understand how to embrace a notion such as emergence in complexity, show us how to use complexity to inform our social and our work lives, leverage the self-organizing capabilities of complex adaptive systems to achieve personal and organizational goals, and apply metaphors from chaos and other complexity-oriented theories to better describe and understand our world. We look forward to publishing the best work in these areas and in others that will surely emerge.

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