Cybernetics and Systems: An International Journal, 45:547–567

ISSN: 0196-9722 print/1087-6553 online
DOI: 10.1080/01969722.2014.945315

Co-Evolution Path Model (CePM): Sustaining Enterprises as Complex Systems on the Edge of Chaos

HADI KANDJANI[1,2], MADJID TAVANA[3,4], PETER BERNUS[5], and SUE NIELSEN[6]

[1]*Department of Information Technology Management, Faculty of Management and Accounting, Shahid Beheshti University, Tehran, Iran*
[2]*Centre for Enterprise Architecture Research and Management, Institute for Integrated and Intelligent Systems, School of Information and Communication Technology, Griffith University, Australia*
[3]*Business Systems and Analytics Department, Lindback Distinguished Chair of Information Systems and Decision Sciences, La Salle University, Philadelphia, Pennsylvania, USA*
[4]*Business Information Systems Department, Faculty of Business Administration and Economics, University of Paderborn, Paderborn, Germany*
[5]*Centre for Enterprise Architecture Research and Management (CEARM), School of ICT, Griffith University, Brisbane, Australia*
[6]*Institute for Integrated and Intelligent Systems (IIIS), School of ICT, Griffith University, Brisbane, Australia*

The purpose of this study is primarily theoretical—to propose and detail a model for system evolution and show its derivation from the fields of enterprise architecture (EA), cybernetics, and systems theory. Cybernetic thinking is used to develop the coevolution path model (CePM) to explain how enterprises coevolve with their environments. The model reinterprets Ashby's law of requisite variety, Stafford Beer's viable system model, and Conant and Ashby's theorem of the "good regulator" to exemplify how various complexity management theories could be synthesized into a cybernetic theory of EA—informing management of mechanisms to maintain harmony

Address correspondence to Madjid Tavana, Business Systems and Analytics Department, Lindback Distinguished Chair of Information Systems and Decision Sciences, La Salle University, Philadelphia, PA 19141, USA. E-mail: tavana@lasalle.edu

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ucbs.

between the evolution of the enterprise as a complex system and the evolution of its complex environment.

KEYWORDS coevolution path model (CePM), complexity, cybernetics, edge of chaos, enterprise architecture (EA)

INTRODUCTION

The increasing complexity of the IT and business environment and the need to ensure alignment of IT with business goals and operations have given rise to a number of initiatives in information systems research and practice (Luftmann and Kempaiah 2007). Prominent among these is the discipline of enterprise architecture (EA), which is now widely accepted as a requirement for high-level and comprehensive management of the IT enterprise (Ross and Well 2006; Winter and Sinz 2007; Winter and Fisher 2007). Despite this acceptance, the field of EA is still developing, elaborating, and harmonizing various theoretical frameworks and models. This study aims to contribute to this work by exploring the application of cybernetic thinking to explain how systems coevolve with their environments. A coevolution path model (CePM) is developed, which reinterprets "System 4" of Beer's Viable System Model (Beer 1985), i.e., the system that is responsible for strategically steering the organization.

We derive this theoretical model from the fields of EA, cybernetics, and systems theory. Although the CePM model is in its early stages of development and has yet to be tested in empirical studies, both "testable propositions and causal explanations" (Gregor 2006) are proposed for real-life applications.

We use the Generalized Enterprise Reference Architecture and Methodology (GERAM) framework (Bernus and Nemes 1996; IITF 1999; IITF 2003; ISO15704 2000, AMD 2005) as a basis for the model, because of its "agnostic" nature and its important concepts of Life History and Life Cycle. GERAM defines a comprehensive set of concepts to represent and explore enterprise evolution. GERAM is a "toolkit of concepts for designing and maintaining enterprises for their entire life history" and the objective of this framework is "to systematize various contributions of the field that address the creation and sustenance through life of the enterprise as a complex system" (IITF 1999). GERAM is different from frameworks developed for only pragmatic purposes; pragmatic frameworks do not necessarily have to make certain theoretically important differentiations, nor do they have to be complete in every respect to be usable for some particular practical EA project. However, fundamental conceptual differentiations and domain completeness are needed to create a foundation of what we call "EA Cybernetics" in order to interpret models of evolution and management. Although many frameworks could be made complete by satisfying all GERAM (ISO15704) requirements (Bernus et al. 1996; Noran 2003), we use GERAM's concepts because they have the properties that we need to develop our model.

From a practical standpoint, the proposed model (CePM) might enable enterprises to recognize the signs of dissonance between system complexity and environment complexity and as a result make deliberate decisions to steer away from system states that are on the edge of (perceived) chaos and from trends toward obsolescence. This article also proposes the development of an EA cybernetics framework that can equally represent evolutionary and deliberate/designed changes.

Note that there are two forces at work: a system needs to be able to display enough complex behavior to respond to the needs of (or survive in) the environment; at the same time, excessive complexity makes the system difficult to control. Critical issues include how complexity can be measured and how excessive complexity can be eliminated. One important complexity measure is the system's information content, as defined by the system's Kolmogorov complexity (KC; Li and Vitányi 2008). For example, the authors previously demonstrated (Kandjani et al. 2012), how known approximation methods of KC can be used to estimate the information content of a system and how this can be utilized to make architectural design decisions to "design out" excessive complexity from a supply chain.

The remainder of this article is organized as follows. "Complexity and the Cybernetics Perspective" briefly discusses the complexity problem in enterprises and some relevant disciplines applied to EA such as cybernetics and management cybernetics to tackle such a problem. "Enterprise Architecture" introduces EA cybernetics as a distinct field of the EA discipline, which invokes theories, terminologies, and reference models from systems thinking and cybernetics: harmonizing, synthesizing, systematizing, and formalizing the results of such contributions and applying them as EA practice. "The CePM: Dynamic Homeostasis vs. Dynamic Heterostasis" introduces an EA cybernetic model, the CePM, and discusses how enterprises as complex systems should coevolve with their complex business environments. "Coevolution Mechanisms: Order, Complexity, and the Edge of Chaos" further explains the CePM model and describes coevolution mechanisms, using positive and negative feedback, and visually demonstrates state transitions of enterprises as complex systems in four system paths. The final section presents our conclusion and future research directions.

COMPLEXITY AND THE CYBERNETICS PERSPECTIVE

Enterprises are best understood as intrinsically complex adaptive living systems: they cannot purely be considered as "designed systems," because deliberate design/control episodes and processes ("enterprise engineering," using models) are intermixed with emergent change episodes and processes (which might perhaps be explained by models). The mix of deliberate and emerging processes can create a situation in which the enterprise as a system is in dynamic equilibrium (for some stretch of time)—a property studied in General Systems Theory (von Bertalanffy 1968).

The evolution of the enterprise (or enterprises, networks, industries, the entire economy, society, etc.) includes the emergent as well as the deliberate aspects of system change, therefore, we believe that EA needs to interpret previous research in both areas. This is summarized as the main aim of the EA discipline and practice, i.e., to explain change in enterprises as complex systems (through theory, models, and methodologies; Kandjani and Bernus 2011a).

In response to the problem of managing complexity and rapid change, many studies applied the cybernetic perspective to EA (application of cybernetic concepts to EA management; Buckl et al. 2009) and to EA principles, e.g., as embodied in The Open Group Architecture Framework (TOGAF; EsmaeilZadeh et al. 2012)).

Stafford Beer believed that the dynamics of enterprises is about "the manipulation of men, material, machinery, and money: the four Ms," but it is also about a fundamental manipulation of systems, which we call the "management of complexity" (Beer 1966, 1985).

Wiener (1948) defined cybernetics as "the science of control and communication in the animal and machine." Ashby calls it the art of "steermanship": the study of coordination, regulation, and control of systems; and argued that "truths of cybernetics are not conditional on their being derived from some other branch of science" (Ashby 1956).

Therefore, the field embraces a set of self-contained groundings and foundations (Ashby 1956). Ashby addressed the complexity of a system as one of the peculiarities of cybernetics and indicated that cybernetics must prescribe a scientific method of dealing with complexity as a critical attribute of a system.

Beer was the first person to apply cybernetics to management and defined cybernetics as "the science of effective organization" (Beer 1959; Jackson 2000). He was also first to coin the word "Management Cybernetics" —a field applying cybernetic laws and theories to all types of sociotechnical organizations/"enterprises" (Ramage and Shipp 2009).

Beer elaborates on the relevance of cybernetics to management in *Cybernetics and Management* (Beer 1959) and describes his first discoveries and promises in the management discipline. He also characterizes cybernetics as "the science of control" and management as "the profession of control" (Beer 1966).

Therefore, EA research has acknowledged the relevance of cybernetics for modern enterprises, which cannot expect to build "ideal" and one-time systems but must undertake continuous steering and control of their evolving systems (Schmidt and Buxmann 2011). Such a perspective elaborates on Beer's "systems 3, 4, and 5" to cope with the increasing complexity of enterprises and their environments.

ENTERPRISE ARCHITECTURE CYBERNETICS

One common topic of cybernetics is the treatment of complexity (whether it is the complexity of the structure, behavior, control, management, or other relevant view of the system of interest), raising the question, How can systems be managed, controlled, changed, designed, or partially influenced for producing emergent adaptive behavior?

A distinct problem and characteristic of complex systems is that none of these tasks can be based on a completely predictive model, and therefore the necessary decisions must be based on incomplete information. Because of this property of complex systems, we need theories and methods—or structures—that produce such self-control behavior (either in a deliberate or in an emergent way). This can be observed as "partial control," which nevertheless achieves a set of valued system properties (such as sustainability, viability, availability, etc.).

For that reason, any controller (on any level of a complex system) has only, or can have only, an incomplete model of the system and makes decisions to control the system based on the perception using this incomplete model. The complexity of a model such as this represents the "apparent complexity" of the system from the given controller's (manager's) point of view.

Checkland warns that theories, frameworks, and models with an excessive level of abstraction and general systems principles of "wholeness" could be deficient in dealing with practical situations (Checkland 1999). At the same time, there exist very specific context-dependent theories, frameworks, and models that sacrifice generality and abstraction, although there is often little guidance on the limits of their applicability. The optimum degree of generality is somewhere between, with different levels of abstraction for each purpose. For example, General Systems Theory (von Bertalanffy 1968) cannot be applied by using a single science discipline in isolation (Boulding 1956).

In order to develop a model that might explain how systems coevolve with their environments, we have adopted fundamental concepts of the Generalized Enterprise Reference Architecture and Methodology (GERAM) framework (IITF 1999).

EA frameworks such as GERAM acknowledge that the optimum degree of generality is problem-domain dependent; therefore, it is necessary to provide a modeling framework that represents this continuum from the most generic to the most specific.

GERAM defines

1. Generic Enterprise Modelling Concepts (GEMCs): practically ontological theories
2. Partial Enterprise Models (PEMs): usually in the form of reference models

3. Particular Enterprise Models (EMs): GEMCs define and formalize the most generic concepts of enterprise modeling, PEMs capture characteristics common to categories of enterprise entities within or across one or more industry sectors, and particular enterprise models (EMs) represent a particular enterprise entity (IITF 1999).

EA Cybernetics must maintain an optimum degree of generality to provide the discipline and practice with the right level of abstraction for each purpose; whereupon, given the abstract theory and a concrete system (and concrete problem), there should exist methods that can be used to solve or explain the problem within the limitations of available resource and time constraints.

EA, as a developing discipline, needs a model for theory development, testing, and knowledge creation. Anderton and Checkland (1977) developed a model of any developing discipline to demonstrate the cyclic interaction between theory development, problem formulation, and theory testing (Anderton and Checkland 1977; Checkland 1996). For EA to be a developing discipline, we consider real-world, enterprise-problem domains as the source of a development process, to be addressed by theories, models, and methods in enterprise-related disciplines.

The following will shape ideas by which two types of theories could be developed (Checkland 1996):

1. substantive theories derived from related disciplines to apply relevant models, theories, and methods in the problem domains, and
2. methodological theories about how to individually apply enterprise-related disciplines in the problem domains.

Once we develop such theories, it is possible to state problems—not only existing problems in concrete enterprise-problem domains —but also formalized, harmonized, and synthesized problem statements by EA cybernetics within a new theory.

As a new theory, EA cybernetics produces formalized enterprise-problem domains, which may be represented using the unified cybernetic theory of EA. These unified theories could be used to develop methodologies to be used in EA practice.

Results of such synthesis must be tested in practice (through intervention, influence, or observation) to create case records, which in turn provide the insight to develop better theories (and better models, techniques, and methodologies). The application of the latter methodologies should be documented in case records that provide feedback to improve the unified and the individual theories.

The EA discipline not only embraces the models, methods, and theories of management and control but also those of systems engineering, linguistics, cognitive science, environmental science, biology, social science, and artificial intelligence.

Cybernetic thinking can provide a method of unifying (and relating) the contribution of these disciplines as well as represent the essence of multiple theories using abstract functions and processes (and metaprocesses) and their relationships, rules, and axioms (likely to be expressed in suitably selected logics).

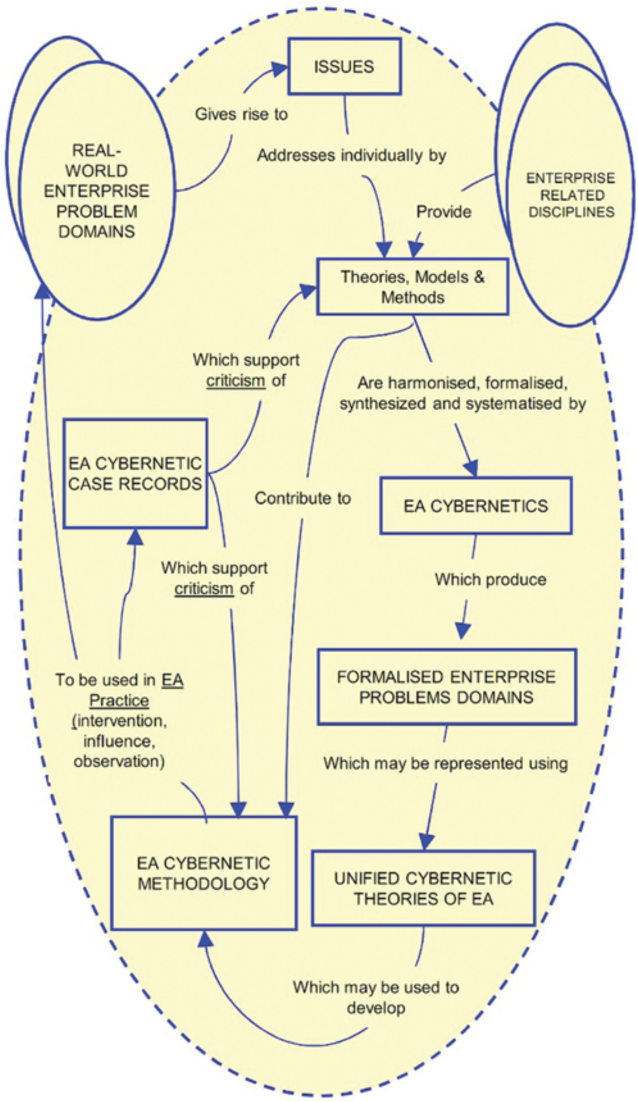

FIGURE 1 Enterprise architecture as a developing discipline based on the model of activities and results of developing disciplines.

Figure 1 shows the pathway through which the rapport of these disciplines is formalized, synthesized, harmonized, systematized, and eventually represented as a unified cybernetic theory of EA. The CePM introduced in the next section is an example of a cybernetic model of the control and management of viable complex systems that operate in complex environments.

THE CEPM: DYNAMIC HOMEOSTASIS VS. DYNAMIC HETEREOSTASIS

A key property of a viable system and a "measure of its submission to the control mechanism" is its ability to maintain homoeostasis, defined by Beer (1966) as "constancy of some critical variable (output)."

In our model of coevolution, we demonstrate the dynamic sustenance of requisite variety based on Ashby's law: "only variety can destroy variety" (Ashby 1956). As paraphrased by Beer (Beer 1979), "variety absorbs variety," where "variety" is the number of possible states of a system (Beer 1981), or recently clarified as the number of *relevant* states of a system (Kandjani and Bernus 2011b).

In order for a system to dynamically achieve and maintain requisite variety and to be in dynamic equilibrium, the system requires communication channels and feedback loops. These communication channels serve as self-perpetuating mechanisms that include both attenuation and amplification mechanisms. (Note that for the discussion following, a system includes the system's controller.)

Considering the system and its environment as two coupled entities, the effect of perturbing one component on the other component is either amplified through positive feedback, or reversed (attenuated) through negative feedback.

The role of a negative feedback loop is to reverse the effect of the initial perturbation and restore system homeostasis (in which critical variables are stable) whereas positive feedback can create unstable states (Ashby 1940).

We observe that both a system and its environment (including systems in that environment) evolve, and this can create an imbalance between the requisite variety (maintained by the controller) of the system and the variety that would be required for it to maintain homeostasis. In other words, systems that want to live long must coevolve with their environment.

Formally: we consider the environment an entity with a possible set of observable states, and if two such states require different responses from the system, then the system must be able to differentiate between them; thus, they are two different relevant states. (Note: we might not be able to describe the environment as a system, although it may contain one or more systems.)

Consequently, in Figure 2, the complexity of a system (C_S) is defined to be the complexity of the model the controller of the system maintains (or

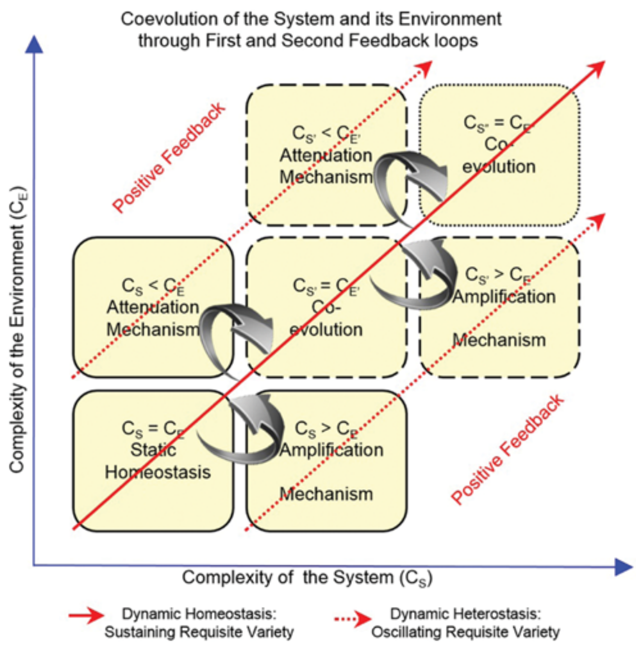

FIGURE 2 The coevolution path model.

appears to be maintaining) in order to manage the system's operations—including the need to interact with the environment.

The complexity of the system's environment (C_E) is a relative notion and is defined to be the complexity of the model of the environment that the controller of the system would need in order to maintain the system's homeostasis; although, to an outside observer, it is sufficient if the system's controller *appears* to be maintaining such a model.

Specifically, an "environment model" must have predictive capability, so that the system, while interacting with its environment, can maintain a homeostatic trajectory. An environment model would thus include as components: (1) models of external systems with which our system interacts (including models of their controllers and operations), and (2) a model of the rest of the environment, in order to be able to represent and predict the states of signals and resources in the system, the external systems, and the rest of the environment, Based on the theorem of the "Good Regulator" (Conant and Ashby 1970), a good controller of a system must have a model of that system with an equal complexity as the system itself.

In Figure 2, notice that

1. If the complexity of the system (C_S) equals that of its environment (C_E), then the system has the requisite variety and is in static equilibrium. However, any change in the complexity of the environment should be sensed

by the system's self-perpetuating mechanism in order to restore the system to its initial state or to create a new equilibrium state.
2. If the complexity of the environment is greater than that of the system, then the system should attenuate the effects of this complexity, i.e., change and coevolve with its environment (in other words, this happens when the environment produces, or is recognized to have the potential to produce, states in which the system cannot function as expected).
3. If the complexity of the system is greater than that of its environment, then the system can potentially create a set of different states and perform behaviors that are not differentiated by its environment. The system can identify this extra complexity as undesired, or use an amplification mechanism to create new differentiations in the environment (e.g., marketing of new goods/services).

If a new enterprise lacks coevolution mechanisms, then it might be viable in the short term, but doomed in the long term. Such failure of enterprises is attributable to the inflexibility of their business models, due to the lack of attenuation and amplification mechanisms to sustain dynamic stability. This is why, according to Badalotti (2004), the new economy's most successful start-ups have changed their business models several times in the first few years of their existence.

A successful example is America-On-Line (AOL), which initiated its business and grew as an Internet Service Provider, but re-identified itself as a content provider, redesigning its business model and market positioning (Badalotti 2004).

The CePM has a level of abstraction that makes it applicable to any change and coevolution of a complex system in its environment. In this study, we use concepts of GERA and its modeling framework because they provide us with a comprehensive coverage of the possible changes.

Using GERA concepts and viewpoints, the controller (manager in charge of the system) could

1. model and steer, in light of change in the environment, by taking into account relevant viewpoints of the environment's model, and
2. design coevolution mechanisms to change or manipulate the system's operations, using a relevant combination of models, viewpoints, and life-cycle processes, as well as design a change trajectory in the system's life history.

For example, one could use the Strategic Alignment Model (SAM) by Henderson and Venkatraman (1993) and map it to the CePM: i.e., use SAM as a change/coevolution model of the enterprise and its environment, using IT- and business-related viewpoints of our adopted modeling framework.

COEVOLUTION MECHANISMS: ORDER, COMPLEXITY AND THE EDGE OF CHAOS

In this section, we demonstrate the transitions caused by changes in the complexity of a system (C_S) and the complexity of its environment (C_E), and relevant mechanisms to keep the system in equilibrium.

Coevolving/Viable System States

Consider the system in state 1 as its initial state where (approximately) $C_S = C_E$; i.e., the system is in a homeostatic state, as shown in Figure 3. If there is an increase in C_E from state 1 to 2 (such as the introduction of a substitute product or service to the market by a rival company) then this moves the company into the vulnerable zone.

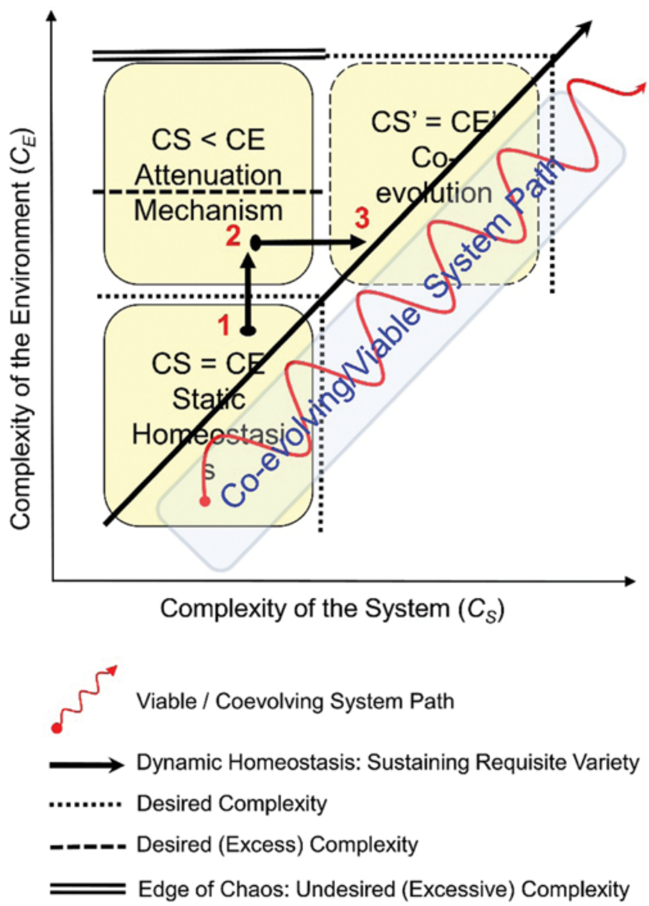

FIGURE 3 Traces (path) of coevolving/viable system states.

In order for the system to adapt to the changes in the environment and achieve the requisite variety and remain on the viable path, it always needs some excess (but not excessive) complexity.

There are two different complexities here: the variety of the system and how the system achieves that variety (for instance, by the reconfiguration of its structure, acquiring more resources, creating new capabilities, reducing production costs, or innovating a new product or service).

Such adjustments that take into account new differentiations (and thereby variety) in the environment will move the company from state 2 to state 3, where C_S equals C_E and the company remains on the coevolving/viable system path.

The history of manufacturing has typical examples of this effect. The initial manufacturing lines of mass production in the car industry were able to produce only a low variety of products, and as the environment evolved, differentiated customer requirements made the market more sophisticated, and companies with mass production systems were unable to respond to this new complexity. Approximately 15–20 years after World War II, manufacturing companies realized that greater flexibility was needed in terms of the variety of products that a manufacturing system could produce.

From the mid-1970s to the mid-1980s, integrated manufacturing systems were built that had numerically controlled (NC) machines, whereby the same machine would be able to perform many manufacturing operations (limited by the basic functions of the machines in the system). However, these integrated systems were not easy to change, i.e., whereas the complexity of responses of these systems to market needs were far greater than those of transfer lines, incremental changes were not possible. Thus, after a while these systems could not respond to changes in the environment's requests, and they died out.

For the (manufacturing) system to be able to keep coevolving with the environment, the next generation of flexible (cell-based) manufacturing systems (Fine and Freund 1990) had to be developed (using the group technology paradigm). These systems were able to be incrementally developed, old cells decommissioned and new cells added, as the needs of the environment dictated. The development gave rise to the manufacturing agility movement (1990s). This moved the center of attention from the capability of the single company as a system to the network of enterprises that can create the requisite variety in a dynamic fashion, by forming so-called virtual enterprises on demand (Iacocca Institute 1991; Goldman et al. 1995). Another example from the continuous (small batch) chemical production industry is the "pipeless" chemical factory invention (Okuda et al. 1997). The complex demands of the market are impossible to meet cost-effectively by a conventional fixed-pipe factory, where the variety of ways the production equipment can be used to channel products is limited. The pipeless factory allows any equipment to be interconnected with any other equipment, using a robot-controlled flexible piping system, increasing the complexity of the behavior of the chemical factory.

Inefficient System States

Now consider the state in which the system has, or acquires, excessive resources and capabilities (a set of potential structures and ability that could perform functions that are not completely invoked by the system's environment).

This transition from state 4 to state 5 can create undesired or unnecessary (excessive) complexity, as shown in Figure 4. For example, a manufacturing company (in state 4) with a leading R&D department designs a new product, the inbound logistics provides necessary goods and materials and finally the company establishes its production line (state 5). However, if the market is not ready for such product differentiation, the company has excessive, and therefore undesired, complexity.

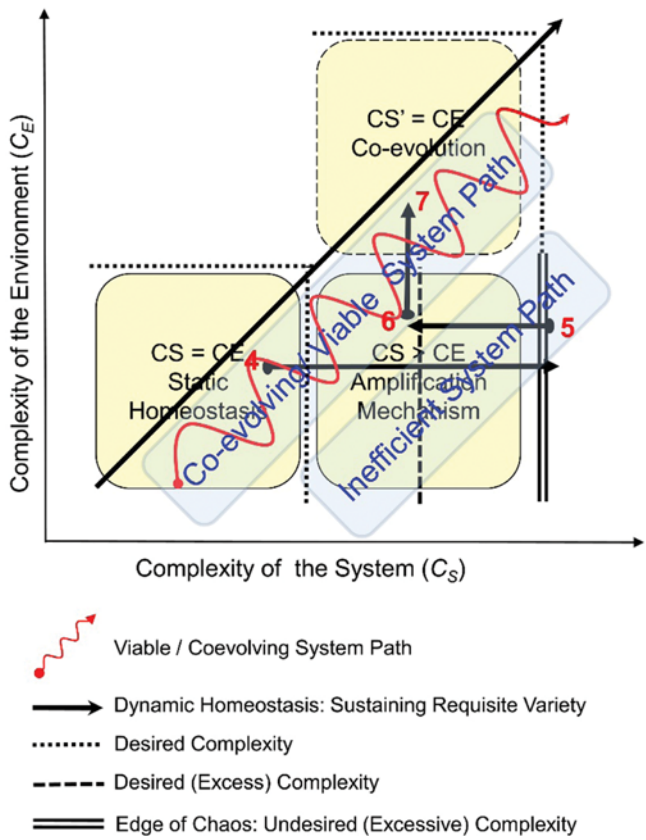

FIGURE 4 Traces of inefficient system states.

Because the controller (management) has difficulty being able to predict what level of complexity the market/environment will embrace, there must exist mechanisms to recognize and curtail excessive systems' complexity.

To reduce the potential risks and inefficiency of this new venture as a new potential structure and to increase the probability of success when designing change projects, this company should apply complexity reduction techniques such as Axiomatic Design (Suh 1990, 2001, 2005) to reconfigure its functions, structures, and architectures to shift from the inefficiency zone to achieve effectiveness and efficiency in state 6, where the company has some desired excess complexity but eliminates excessive complexity.

At this stage, the company still has excess complexity, which should be conditioned to the market ("the environment"), and therefore, the marketing department should apply effective marketing strategies in order to introduce the new product to the market and promote its sales.

Having developed and implemented a successful marketing strategy and plan, the manufacturing company adjusts its excess desired complexity caused by new structures and ends up in a new homeostatic state (state 7).

For example, many Japanese electronic goods manufacturers usually release a wide variety of products domestically, to test customer reaction and, based on the market response, often reduce the variety of products before marketing them worldwide and simplifying the supply chain for global production. Such companies compete on variety being released to the market quickly (Stalk 1988), while carefully managing *how much* variety they offer, *when*, and *where*.

Vulnerable System States

Let us consider the state where there is an increase in the complexity of the environment, as shown in Figure 5 (state 8 to 9).

For the system to respond to the changes in C_E and achieve requisite variety (and a new homeostasis) and remain viable, it needs to attenuate more complexity and coevolve with the environment.

For example, rivals can reduce the company's market share by introducing new or substitute products and, therefore, the company is at risk of losing its competitive advantage. The company has no other choice than to reconfigure its current resources and structures, or to acquire more resources and potential structures to create new capabilities/competencies and re-vitalize its competitive advantage (perhaps merging with other companies to survive: state $9 \rightarrow 10$).

Unfortunately, state transitions from state 9 to 10 usually impose excessive complexity on the company; e.g., companies may underestimate the integration tasks in horizontal mergers and can end up with an inefficient operation preventing them from enjoying the benefits of the merger (Mitleton-Kelly 2004). Therefore, to avoid inefficiency and to mitigate the risks of establishing

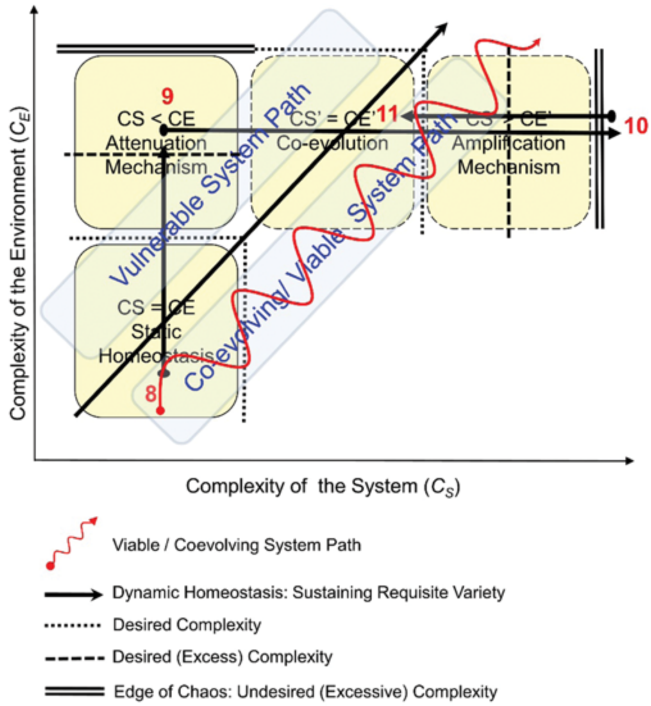

FIGURE 5 Traces of vulnerable system states.

a new production line (new structures and capabilities, creating undesired excessive complexity), the R&D department/the design authority should apply complexity reduction methods and techniques such as "Extended" Axiomatic Design Theory (EAD) (Kandjani and Bernus 2011b).

EAD deals with reducing and possibly avoiding the complexity of the change process, which designs and implements necessary changes (such as the establishment of a new production line). Using this method, the company may avoid the inefficiency zone and remain in the viable zone.

The spiral arrow in Figure 5 demonstrates the viable system path in which the system dynamically sustains its homeostasis and avoids or rectifies inefficient and vulnerable states by invoking relevant attenuation and amplification mechanisms.

Nonviable System States

Let us now consider the states where the company will not remain viable (as in states 12 to state 13, shown in Figure 6). Enterprises as live systems have a number of variables characterizing essential survival properties. Ashby (1960) refers to these as "essential variables" (crucial to a system's

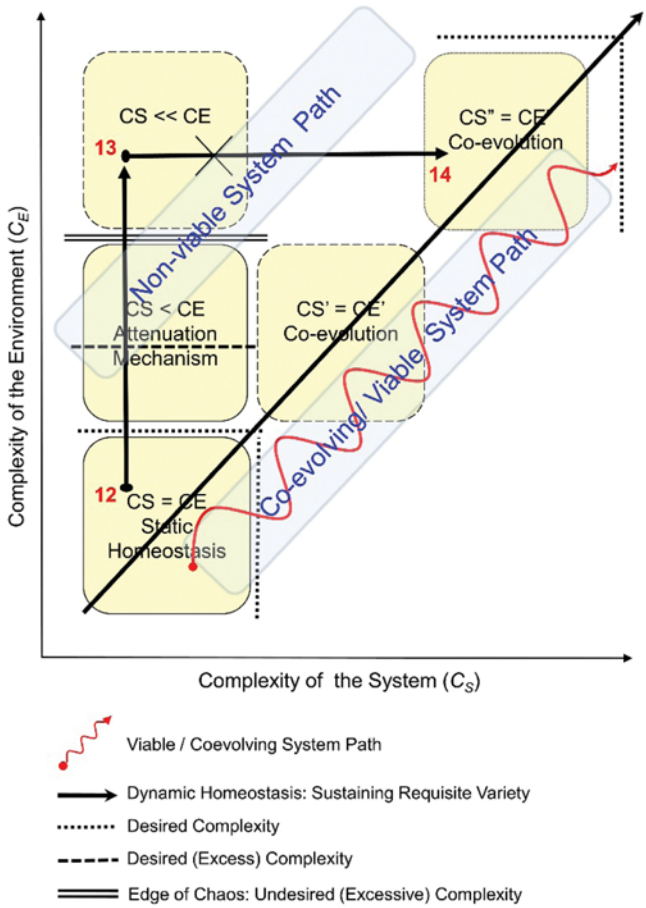

FIGURE 6 Traces of nonviable system states.

survival)—modern literature would refer to these as strategic "key performance indicators."

Ashby defines survival as "... a line of behavior [that] takes no essential variable outside given limits" (Ashby 1960; Geoghegan and Pangaro 2009). Therefore, by definition, any line of behavior outside the limits of essential variables is on the nonviable system path and is fatal to the system's lifeline.

For a system to be regarded as adaptive, and therefore viable, Ashby introduces two necessary feedback loops (Ashby 1960; Geoghegan and Pangaro 2009; Umpleby 2009). The first frequently operating loop makes small modifications and corrections to the system. The second loop in fact changes the structure and architecture of the system when the tolerance of the essential variables (invoked by dramatic changes in the system's environment) falls (or is predicted to be falling) beyond the limits of survival. If the system's second loop does not respond to the changes in complexity of the environment, then the system will be on the nonviable path.

Based on Ashby's theory of adaptation (1960), Umpleby (2009) indicates that the first feedback loop is necessary in order for a system to learn a pattern of behavior that is necessary for a specific environment, whereas the second feedback loop is required in order for a system to identify the changes in the environment and design and create new patterns of behavior.

If there is a dramatic increase in complexity of the environment (as in states 12 to state 13) it is possible that the system is not prepared to react because of scarcity of resources, lack of dynamic capability, inability to create new structures in a timely manner and adapt its architecture to the change in the environment.

The lack of an appropriate second feedback loop makes the system nonviable and the system is doomed to fail. In this state, the company could save itself by establishing a partnership or merger (a reactive move, where the system relies on another system for rescue).

In summary, we can classify system states into four groups in terms of coevolvability/viability:

- Nonviable System states (states: 12-13-14)
- Vulnerable System states (states: 8-9-10-11)
- Inefficient System states (states: 4-5-6-7)
- Coevolving/viable System states (states: 1-2-3)

Viability and EA Cybernetics

The theory of viable systems argues for the need of a controller in a system (system 4) to monitor the environment, in order to predict the need for change and steer the system away from a nonviable trajectory. However, apart from the structural imperative, there is no theory or method proposed for this controller to use.

Ashby's law gives an argument for this system's existence (because the system is meant to be able to have enough variety in order to remain viable), however, no method or theory is given to achieve this or to measure variety. The two theories are even seemingly in contradiction, because although Ashby requires the system to have more variety than the environment, Beer points out that the system can never have a complete model of the environment. The CePM removes this contradiction as it considers the system dynamics of evolution.

The first consequence is that the system (and its controller) need to have only a *view* of the environment to differentiate *relevant* states (Kandjani and Bernus 2011b), thus the complexity of the model that the system needs to have of its environment is not the same as the complexity of the model of the environment that an omniscient observer would see. This allows the system to prepare for a future unknown and unpredictable states of its surroundings, because the controller needs only partial proof about the future states of the environment.

For example, the manufacturing company is unable to predict exactly what products will be needed in the medium term, but it still can predict that all future products would be based on a number of known technological elements (given what is feasible today in the research laboratories). Thus, the great number of actual combinations of product features do not add to the complexity of states of the environment.

The second consequence of the CePM is that it makes the imperative of excess complexity reduction explicit. The recognition of the need, combined with complexity estimation methods (Kandjani et al. 2012) and a complexity reduction methodology (using the extended axiomatic design; Kandjani and Bernus 2011a), forms a synthesis of several disciplines, each contributing to the maintenance of a system on a viable path.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

We proposed CePM using cybernetic principles to explore and map how enterprises might manage complexity in light of (anticipated) changes in the environment. In proposing this model, it is understood that it is not possible to create complete models of large-scale complex systems (such as an enterprise) or of the environment and use them to fully control the system.

It is clear that we must accept incomplete models of the complex systems that we want to control. Second, we must consider that when living organisms (such as people) are part of a system, their actions are not completely dictated by the system they are part of, nor are they necessarily guided by logic. Power relations, survival, self-interest, group-interest, value systems, culture, etc., are all participating in determining how a system "plays out," in other words, however logical the design of a system might be, relying only on the logic of processes is insufficient.

The discipline of cybernetics developed fundamental theories of complexity, and therefore, the authors propose EA Cybernetics as a subdiscipline of EA, aiming to synthesize and harmonize the many pertinent cybernetic models developed over the past 50 years and apply them in the field of EA.

EA cybernetics is the reinterpretation of old and new theories in order to understand their individual contributions and to point at the need for genuinely new results. Cybernetic thinking provides a method of unifying/relating the rapport of multiple disciplines. We expect that a synthesis would yield a new, unified cybernetic model of EA, and more powerful theories, reference models, and methodologies than we have today, both in the problem domain and at the meta-level (discipline development). We developed an EA cybernetic model called the CePM that reinterprets Beer's Viable System Model (based on Ashby's requisite variety law and first and second feedback loops) demonstrating how systems can dynamically sustain their own viability.

We believe that future research that explores the human and organizational implications of the cybernetic perspective would be useful when studying enterprises as complex systems. Future research should focus mostly on the application of the CePM in real-world examples of competitive behavior in a market demonstrating the trajectory of the system driven by a strategy to achieve an efficient matching of complexity with competitors in a particular market; too much complexity for a particular market ($C_S > C_E$) is too costly; too little complexity is inadequate for survival ($C_S < C_E$) and it could take the system out of the market. The proposal is to examine and steer the system–environment interactions along the coevolving viable system path, where C-system • C-environment (we use the sign "$\approx$", approximately equal to) because the desirable state is that in which system complexity is slightly higher than the apparent complexity of the environment, because the system needs time to delay to act on changes (or anticipated changes) in the environment. In the language of competition: where the system is identifying new competitive challenges (e.g., new or upcoming competitors) and makes adjustments to match current or anticipated performance demands.

REFERENCES

Anderton, R. H. and P. B. Checkland. *On Learning Our Lessons* (Internal Discussion Paper). Lancaster, UK: Department of Systems, University of Lancaster, 1977.

Ashby, W. R. "Adaptiveness and Equilibrium." *The British Journal of Psychiatry* 86, no. 362 (1940): 478–483.

Ashby, W. R. *An Introduction to Cybernetics*. London: Chapman & Hall, 1956.

Ashby, W. R. *Design for a Brain; the Origin of Adaptive Behavior*. New York: Wiley, 1960.

Badalotti, E. "New Economy, Complexity and Management. Complexity Theory and the Management of Networks." In *Workshop on Organisational Networks as Distributed Systems of Knowledge*, edited by P. Andriani and G. Passiante, 59–64. London: Imperial College Press, 2004.

Beer, S. *Cybernetics and Management*. New York: Wiley, 1959.

Beer, S. *Decision and Control: The Meaning of Operational Research and Management Cybernetics*. New York: Wiley, 1966.

Beer, S. *The Heart of Enterprise: The Managerial Cybernetics of Organization*. New York: Wiley, 1979.

Beer, S. *Brain of the Firm* (2nd ed.). New York: Wiley, 1981.

Beer, S. *Diagnosing the System for Organizations*. New York: Wiley, 1985.

Bernus, P. and L. Nemes. "A Framework to Define a Generic Enterprise Reference Architecture and Methodology." *Computer Integrated Manufacturing Systems* 9, no. 3 (1996): 179–191.

Bernus, P., L. Nemes, and T. J. Williams. *Architectures for Enterprise Integration*, 368. London: Chapman and Hall, 1996.

Boulding, K. E. "General Systems Theory-The Skeleton of Science." *Management Science* 3, no. 3 (1956): 197–208.

Buckl, S., F. Matthes, and C. M. Schweda. "A Viable System Perspective on Enterprise Architecture Management" In *Proceedings of the 2009 IEEE International Conference on SMC*, 1483–1488. San Antonio, USA: IEEE, 2009.

Checkland, P. *Systems Thinking, Systems Practice*. Chichester, UK: John Wiley & Sons, 1996.

Checkland, P. *Systems Thinking*. New York: Oxford University Press, 1999.

Conant, R. C. and W. R. Ashby. "Every Good Regulator of a System Must be a Model of That System." *International Journal of Systems Science* 1, no. 2 (1970): 89–97.

Fine, Ch. H. and R. M. Freund. "Optimal Investment in Product-Flexible Manufacturing Capacity." *Management Science* 36, no. 4 (1990): 449–466.

Geoghegan, M. C. and P. Pangaro. "Design for a Self-Regenerating Organization." *International Journal of General Systems* 38, no. 2 (2009): 155–173.

Goldman, S. L., R. N. Nagel, and K. Preiss. *Agile Competitors and Virtual Organizations: Strategies for Enriching the Customer*. New York: Van Nostrand Reinhold, 1995.

Gregor, S. "The Nature of Theory in Information Systems." *MIS Quarterly* 30, no. 3 (2006): 611–642.

Henderson, J. C. and N. Venkatraman. "Strategic Alignment: Leveraging Information Technology for Transforming Organizations." *IBM Systems Journal* 32, no. 1 (1993): 4–16.

Iacocca Institute. *21st Century Manufacturing Enterprise Strategy. An Industry-Led View* (Vol. 1 & 2). Bethlehem, PA: Iacocca Institute, 1991.

IITF. "GERAM: Generalized Enterprise Reference Architecture and Methodology." Version 1.6.3. IFIP-IFAC-Task-Force, 1999. (Also, in *Handbook on Enterprise Architecture*, edited by P. Bernus, L. Nemes, and G. Schmidt, Chapter 2. Berlin: Springer-Verlag, 2003.)

ISO15704, AMD 2005. (Annex A, GERAM). *Industrial Automation Systems – Requirements for Enterprise-Reference Architectures and Methodologies*, Geneva: ISO TC184.SC5.WG1, 2000. Also available at http://www.ict.griffith.edu.au/~bernus/taskforce/geram/versions/geram1-6-3/v1.6.3.html (accessed August 2013)

Jackson, M. C. *Systems Approaches to Management*. New York: Kluwer/Plenum, 2000.

Kandjani, H. and P. Bernus. "Capability Maturity Model for Collaborative Networks Based on Extended Axiomatic Design Theory." In *Adaptation and Value Creating Collaborative Networks*, edited by L. Camarinha-Matos, A. Pereira-Klen, and H. Afsarmanesh, 421–427. *IFIP AICT* (Vol. 326). Berlin: Springer, 2011a.

Kandjani, H. and P. Bernus. "Engineering Self-Designing Enterprises as Complex Systems Using Extended Axiomatic Design Theory." *IFAC Papers On Line,* IFAC-WCC18 1 (2011b): 11943–11948.

Kandjani, H., P. Bernus, and L. Wen. "Enterprise Architecture Cybernetics for Collaborative Networks: Reducing the Structural Complexity and Transaction Cost via Virtual Brokerage." In *Information Control Problems in Manufacturing*. *IFAC Papers Online*. 14, no. 1 (2012): 1233–1239.

Li, M. and P. Vitányi. *An Introduction to Kolmogorov Complexity and Its Applications* (3rd ed.). New York: Springer-Verlag, 2008.

Luftmann, J. and R. Kempaiah. "An Update on Business-IT Alignment: A Line Has Been Drawn." *MIS Quarterly Executive* 6, no. 3 (2007): 165–177.

Mitleton-Kelly, E. "Co-Evolutionary Integration: A Complexity Perspective on Mergers & Acquisitions." 2004. http://www.triarchypress.com/pages/articles/Co-evolutionary-Integration-a-complexity-perspective-on-ma.pdf (accessed January 2014).

Noran, O. "A Mapping of Individual Architecture Frameworks (GRAI, PERA, C4ISR, CIMOSA, Zachman, ARIS) onto GERAM." In *Handbook of Enterprise Architecture*, edited by P. Bernus et al., 165–210. Heidelberg: Springer-Verlag, 2003.

Okuda, O., K. Shima, and H. Ishibashi. "A Cartridged Piping-Connecting Apparatus, and Connecting System Using the Same." European Patent EP 0567986, issued July 9, 1997.

Ramage, M. and K. Shipp. *Systems Thinkers*. Berlin: Springer, 2009.

Ross, J., P. Weill, and D. Robertson. *Enterprise Architecture as Strategy: Creating a Foundation for Business Execution*. Cambridge, MA: Harvard Business Press, 2006.

Schmidt, C. and P. Buxmann. "Outcomes and Success Factors of Enterprise IT Architecture Management: Empirical Insight from the International Financial Services Industry." *European Journal Information Systems* 20, no. 2 (2011): 168–185.

Stalk, G. "Time - The Next Source of Competitive Advantage." *Harvard Business Review* 66, no. 4 (1988): 41–51.

Suh, N. P. *The Principles of Design*. New York: Oxford University Press, 1990.

Suh, N. P. *Axiomatic Design: Advances and Applications*. New York: Oxford University Press, 2001.

Suh, N. P. *Complexity: Theory and Application*. New York: Oxford University Press, 2005.

Umpleby, S. A. "Ross Ashby's General Theory of Adaptive Systems." *International Journal of General Systems* 38, no. 2 (2009): 231–238.

von Bertalanffy, L. (1968). *General System Theory: Foundations, Development, Applications*. New York: Braziller, 1968.

Wiener, N. *Cybernetics or Control and Communication in the Animal and the Machine*. (2nd rev. ed 1961). Cambridge, MA: MIT Press, 1948.

Winter, R. and R. Fischer. "Essential Layers Artifacts, and Dependencies of Enterprise Architecture." *Journal of Enterprise Architecture* 3, no. 2 (2007): 7–18.

Winter, R. and E. J. Sinz. "Enterprise Architecture" (editorial). *Information Systems and e-Business Management* 5, no. 4 (2007): 357–358.

Zadeh, E. M., G. Millar, and E. Lewis. "Mapping the Enterprise Architecture Principles in TOGAF to the Cybernetic Concepts." *45th Hawaii Int. Conf. on Systems Science HICSS* (4–7 January 2012, Maui, HI), 4270–4276. Washington, DC: IEEE. 2012.