The role of resilience in complex system management: modeling evolution for better engineering

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Abstract. Our contribution is identifying the evolutionary role of resilience within the normal dynamics of an organization. Our approach is essentially epistemological. We think that before giving resilience a practical and methodological meaning, we needed to better understand its sense in the context of observing complex systems like human organizations. Resilience engineering (Re) starts with the observation of systems and requires a reflexive model if its proper role in the observational process is to be understood. Modeling is not just a priority in explaining what resilience is or is not. Much more than that, modeling the observation of evolution in complex systems is a major part of Re itself. Our paper will first introduce our objectives and all the questions we hope to resolve and that we have found in Re literature. Secondly, we will construct our model step by step by introducing and explaining appropriate concepts. Illustrations will lend these key elements meaning. Finally, the role of resilience in this model and the consequences for Re will be examined.

1 INTRODUCTION

Our goal is precisely identifying the role played by resilience into the evolutionary dynamics of an organization. Within the framework of Re, the role of observation in understanding the evolution of a complex system is very important. The way the organizational order appears determines the knowledge we have of it. So when we speak about complex systems, we recognize at the same time that the order of this system is not entirely known to us. We might possibly think that this hidden order (here in the form of the culture of the organization) will never be entirely accessible to us. In any event, the engineer must find a way of approaching this order, thereby grasping certain invariants of the system and some of its hidden internal constraints. Modeling the role of the observation process in the evolution of a complex system can help the scientist reach this goal.

So as to underline the relevance of such an epistemological approach, we will review a series of questions raised in the literature associated with Re. These questions appear to us to provide a good synthetic image of the key elements of this new discipline.

Firstly, it seems important to us to solve certain *recurring paradoxes* in the literature relating to Re, and which involve both descriptive and theoretical analyses. On the descriptive level, the principal paradox is one referring to the capitalist logic of our contemporary organizations, namely associating the contradictory interests of profit-seeking in a free-enterprise context, on the one hand, and security, on the other hand. On the theoretical level, the very concept of resilience regularly shows up at the heart of a paradox often expressed in the following way: “expecting the unexpected” [Epstein, 2008, p. 57] or “be ready for the unexpected” [Hollnagel, 2008, p. 268].

Secondly**,** like others [Dugdale and Pavard, 2008, p. 127], we have noticed a conceptual confusion between the concepts of *resilience* and *robustness* (see, for example, Boissières and Marsden in the Proceedings of the Second Re Symposium réf...). More broadly speaking, this in fact involves the well-known confusion between what Watzlawick et al. of the Palo Alto school of systemic psychotherapy described as being change 1 and 2 [Watzlawick et al., 1974]. Whereas the first type of change is self-preservative and only contributes to maintaining the system in its present and past states, the second type of change is, for its part, able to modify the system in-depth and enable it to reach a new level of operationality `by thinking out of the box'. We can see the difference between resilience and robustness, i.e. between a system captive of itself (of its goals and interests as well as its past and present operating processes) and a open system able to evolve in calling itself into question [Jacques, Laurent, in press]. Included in the first type of change, Re is a function-centred approach. Hollnagel & Woods [2006, p.347] stress this point when they state: “... resilience can be described as a *quality of functioning*.” This quality includes two properties which fit perfectly with our description: “the ability to recover” and “the ability to retain control”.

Thirdly, this distinction between resilience and robustness highlights characteristics specific to the types of complex evolutionary systems we find in life sciences. Nor is it astonishing to find analogies with biological theories of evolution in the literature on resilient engineering. The concept of *adaptation* is particularly well represented, and one finds, for example, citation of the Paleontologist S. J. Gould [Epstein, 2008, p. 57]. Such analogies are not anecdotal and that studying natural evolutive systems like living organisms can help us build a model applicable to evolutive systems like organizations.

Lastly, the importance of *knowledge and information* for Re appears to us to have to be evaluated in the context of the evolutive dynamics of complex systems. The search for information as a key component in the resilient management of a system's security may be poorly understood. On one hand, it is the very insisting on it which leads to the paradox we spoke of earlier. Self-learning on the basis of past experience requires a descriptive effort which itself implies two types of choice: 1) the choice of events which will be used to enrich experience and relies on certain factors (i.e. probability and the number of fatalities), thus eliminating unexampled events [Epstein, 2008, p. 49]; 2) choosing assumptions which guide investigation into past events and limit our capacity to anticipate future risks (Hollnagel's “What-You-Look-For-Is-What-You-Find”, 2008, p. 260). These (non-exhaustive) choices show the extent to which the capacity for anticipation sought for in Re is paradoxical. This problematic is further reinforced by the presence, in the relevant literature, of the concept of *culture*: culture of risk or security. Essentially, culture includes explicit elements (pieces of information and knowledge about the organization's goals and analysis of past experience) and implicit elements (know-how, prudent attitudes and practical experience) about the organization. With information always being the result of a process presupposing an interpretation of choices by observers or interlocutors, the organization cannot count on itself alone to ensure its positive development (maintaining both efficiency in operations and security**).**

So as to treat all these questions, and accounting for the demands they involve (see above), we propose initially designing a model of evolution of complex systems inspired by work done in the life sciences. We shall then describe this model's operation in order to show in its dynamics what corresponds to resilient behavior. Throughout our reflection, we will illustrate the important points of our model in referring to empirical studies published in the literature related to Re.

2 MODELING AN EVOLUTIVE COMPLEX SYSTEM

Our model is based on analysis of living organizations as it emerged, mainly during the seventies, following the development of second cybernetics. By taking the observer into account, the studies of von Foerster, or Atlan, led to a re-evaluation of the concept of information and to a redefinition of the concept of complexity. We will rely basically on Atlan's works and his theory of "complexity from noise" [Atlan, 1972; 1979].

What we thus want to model is the flow of information (in the form of knowledge) between the system and the observer. Let us also recall that the final goal of this modeling will be to show how itself is part of resilience. Indeed, we think that resilience is less a property of the complex system, than a consequence of the engineer's observation of this system with a view to maximize knowledge of it, with a view to decreasing its complexity. We will first present the concepts which make building the model possible. We will then provide an overall picture of it and its evolutive dynamics.

2.1 The basis of any complex system: its redundancy

The crucial concept the model relies on, is 'redundancy'. Its importance in complex living systems is stressed by Atlan, and by the Nobel Eigen [Eigen, 1971; 1992].

Redundancy is the starting point of any organization and corresponds to its formal or formalizable dimension, meaning what is accessible to an observer by means of informations and codes. This involves the redundant or repetitive order, corresponding to what a given system is capable of producing by itself, thus of reproducing. A system's normal activity may be described as a cyclic activity of production or else a routine. One can always find this routine in the intentions of those creating an organization, like a company, as well as in the documents formalizing the company's smooth running (production procedures, rules, contracts, etc).

Seeking the invariants present in an organized system (its internal constraints) is not the same as seeking what is permanent in a static way or what is constantly visible. Its order is dynamic and corresponds to the answers or results it is able to produce and reproduce. We can still talk about redundancy in referring to the *functions* of a system in relation to which a capacity for self-conservation appears. Resilience may appear to be such a capacity for self-conservation, although it is nothing of the sort. Indeed, resilience only appears when the environment the system fits into, is taken into account.

For an open system, interaction with the environment is necessary for redundancy (restocking raw materials, waste evacuation, etc), but such a pairing also necessarily and concomitantly introduces a *risk* taking. Such a system cannot function without taking risks. Hence the organization's security comes to be highly associated with its conservation (redundancy) and always includes at least the following two paired aspects: security of operation (redundancy management) inside the system, and the system's security in its environment (risk management).

The desire and capacity to reproduce an order are for that matter easily recognizable in all organizations. Yet spontaneously the order tends to disappear according to the thermodynamic principle of entropy. However, this reduction in order may be accompanied by an increase in complexity, which we will see more in detail in the next paragraph. Before that, let us see some illustrations of redundancy in organizations.

Redundancy may be observed at several stages in an organization's evolution. The first corresponds to an organization's initial activity, meaning its normal and formalized functional level. The younger an organization is, the more its core is ordered, and the higher the (functional and structural) redundancy therein. A way of measuring this elevated redundancy state consists in measuring the quantity of information (observable) inside the system. It is important to note here that this information is minimal and entirely accessible in a redundant (young) system. In other words, we are dealing with an organization whose culture level (information whose code is inaccessible to an outside-the-system observer) is minimal. The order in which information and codes are accessible to the observer appears to him under the appearance of total redundancy. This order is knowledge because it is deductively repeatable. Atlan explains this by saying “knowledge of an element brings us informations about the others (decreasing uncertainty about them)” [Atlan, 1979, p. 79].

The second stage in observing redundancy coincides with the resolution of a crisis. Here, the quantity of information decreases owing to the fact that a more or less major part of that information becomes incomprehensible for the system. A change has happened, , which makes the normal functioning of the organization inoperative or inefficient. The functioning process usually resorts to minimal and basic routines which amount to a protection mechanism. Such adaptation makes the system turn towards a higher level of redundancy, and is thus accompanied by a loss of information (the latter can be seen i.e. as a loss of coupling or knowledge sharing between the system and its environment). Crisis management in the emergency service of a hospital as studied by Wears [Wears et al., 2008] gives a good illustration of such a phenomenon. Wears show there how space is altered in a crisis. The fact that care areas are recreated in a redundant way in unusual places eloquently expresses the need for intensification of the routines the organization is accustomed to. It is a question of dealing with the surge of new information (on new patients and hence new problems to study and treat) which is not processed individually but collectively. There is a resulting loss of information and an increase in redundancy that corresponds to a typical crisis management mechanism. We shall reconsider further this important aspect of system evolution.

Finally, redundancy can be observed as a means of crisis prevention (avoiding failures), or of reinforcing a central function of the system. It thus seems to be the product of engineering intervening in a system. Hutchins [Hutchins, 1995] has given us an excellent illustration of this type of redundancy (functional reinforcement) as introduced by aeronautical engineering. In fact it shows that crucial information making it possible to land an airplane is provided in redundancy, in space and time, in the cockpit. Andersen and Johnsen (2006) for their part and de Carvalho et al., (2006) for theirs also highlight the importance of redundancy as a preventive function. In itself, it may be considered a way of increasing a system's resilience. We will show that it should better be seen as a differentiation process.

2.2 From redundancy to complexity

What is complexity? Intuitively, we know that complexity is situated between what is perfectly ordered (maximal redundancy) and what is perfectly disordered or chaotic (minimal redundancy). However in building our model we will refer to two other approaches to complexity, those of Atlan and Edelman.

For Atlan, complexity must be recognized as being a negative concept: it corresponds to “the information we don't have about a system”. Hence it is to be associated with the system's entropy, from an observer's viewpoint. Indeed, order only appears in a system if we know it, if we understand the rules, the code, the routines and the formalism behind the fitting together of its elements. “An ordered complexity is thus no longer complex” affirms Atlan [Atlan, 1979, p. 77], while adding that “conversely, not all disorder is necessarily a complexity”. For a disorder to appear complex, it must derive from an order, meaning it is the result of a loss of redundancy. In other words, complexity hides an order we don't know the code to. From the biologist's viewpoint, certain living systems appear extremely complex (human brain) and the somewhat abstruse research work on them consequently proves to be extremely complicated (or even completely uncertain). On the other hand, if we look at a complex organization (i.e. an organization managing the dense air traffic in western skies), the order hidden there is much more accessible. To understand how an ordered system (maximal redundancy) evolves into an increasingly complex system - i.e., less and less knowable - containing more and more information, Atlan brings in the concept of “noise”. We prefer the term system's “degeneracy”, as does Noble prize Gerald M. Edelman.

For Edelman, a system's complexity is highly dependent on its level of degeneracy. Unlike redundancy, which occurs when the same function is performed by *identical* elements, degeneracy, which involves *structurally different* elements (S1, S2, ...), may yield the same or different functions (F1, F2, ...) depending on the context in which it is expressed. Degeneracy is high in systems in which many structurally different sets of elements can affect a given output in a similar way. In such systems, however, degeneracy also can lead to different outputs. Unlike redundant elements, degenerate elements can produce new and different outputs under different constraints. “A degenerate system, which has many ways to generate the same output in a given context, is thus extremely adaptable in response to unpredictable changes in context and output requirements.” [Edelman, 2001, p. 13763].

Degeneracy thus characterizes a complex system having lost part of its redundancy and thus having gained in information. However, this new information is not entirely accessible to the observer. Indeed, it can no longer predict which structures can take part in such a function. In biology, we would speak of differentiation or functional specialization processes. Edelman expresses this in saying that a complex system “reveals an interplay between functional specialization and functional integration”. Let us summarize this in saying that the system has passed from a state of functional *and* structural redundancy to a state of functional redundancy in which a structural diversity has appeared. Such a structural diversification is not mysterious and finds its origin in the very process of repeating basic functional routines. As, for example, Nathanael and Marmaras have proposed in their model [Nathanael, Marmaras, 2008, p. 106], routine practices (redundancy) are modified by exposure to changing environments in which they are repeated. However, it is not the function of these routines which has changed, but the concrete ways of achieving them which have diversified.

It has become clear that it is degeneracy that poses a problem for the observer and thus the engineer wanting to explain the system's behaviors so as to predict them better and thereby improve efficiency. Yet, it is this same degeneracy which makes the system highly adaptive in a changing and unforeseeable environment (i.e., itself complex from the system's viewpoint). Not knowing the system's adaptive causes justifies talking about complexity in its connection. Degeneracy consequently opens up a new dimension in the work of the engineer seeking to measure complexity and who, in so doing, will merely contribute to decreasing it. We will see further on how to measure a system's complexity, given that, in our view, this is the core of Re.

Linking this to the concept of culture seems particularly interesting to us here. A company's culture might well be defined as the knowledge the complex system has about itself and by itself, i.e., on its elementary levels of operation, and which escape any outside look into the system. In other words, the company's culture is its complexity, meaning the knowledge which is only accessible in an empirical way. One would have to take an inside look and participate in the system's operations to garner intimate knowledge of its workings or of its order. But in a world where communication is necessary between such systems, crises are inevitable.

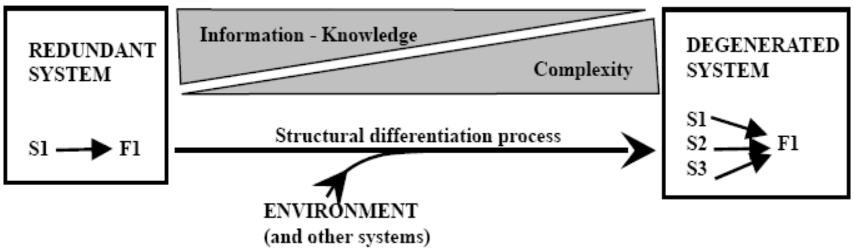

Fig. 1.

2.3 Crises participate in complex system evolution

We now understand that two different, complex systems cannot communicate without having preliminarily made their operating modes public, i.e. without having decreased their complexity. However, if these systems have degenerated, that can prove to be unrealizable.

Let us imagine two non degenerate systems, i.e. perfectly redundant, which intend to communicate. We might, for example, have two computer programming systems that would share all their knowledge. However, if degeneracy is needed so that open systems can evolve in a changing environment, we must also accept the fact that communication cannot be defined as the transparent diffusion of codes and significations. Indeed, this is what we observe with human communication - which is anything but transparent.

Consequently, the coevolution of complex systems (whose environments form part of them) inevitably causes crises. Thus the crises are an integral part of these systems' evolution. A crisis arises when the quantity of information increases inside a system and becomes less and less understandable (decodable, recognizable) by other systems. A complex system is therefore a system which provokes crisis situations. Inevitably, crisis resolution must move in the direction of an improvement in communication, i.e., a reduction in complexity or else an increase in the flow of understandable information between the systems. Hence degeneracy of interacting complex systems does not necessarily decrease (their culture keeps retains its full importance), but new communications tools must be installed and new codes created. A return to a high state of redundancy ineluctably follows (always from the observer's viewpoint). We also understand that this creation of order and thus this new appearance of redundancy signals a relaunching of the system's evolution, i.e. a new potential for differentiation by degeneracy (this is how complexity progresses).

We propose to understand Re as the process which intervenes on the level of creating these new codes, meaning in searching for these new communication formalisms (thus reintroducing redundancy). Its way of solving and anticipating crises makes it an integral part of resilience (see below).

2.4 Exaptation and crisis resolution

We have seen that organizational crises can be considered as resulting from an interruption in communications between one system and another. Let us note that we can apply this crisis model inside one and the same system and consider the interruption in communications between one part of a system and another part of the same system. Communication means the information flow which can be decoded by the interlocutors. In any case, when, from an external viewpoint (the observer's role), the system (or one of its parts) behaves as if a certain order was hidden within it, then such a system can be considered to be complex, and a state of crisis, at least a latent one, exists.

Solving the crisis thus means restoring communication between the systems or the parts of the same system. It is a matter of recovering a part of the information which was lacking for anyone positioning himself as an observer of the crisis situation. It is only in decreasing complexity, i.e., in reassuming a higher level of redundancy, that the crisis will be solved. In our view it is here that Re intervenes and that the very concept of resilience takes on meaning.

Concretely, decreasing complexity means increasing the level of knowledge of the system considered. Moreover this knowledge can be formalized by taking three minimal criteria into account:

1. The *number of different elements* (structures that we note as S1, S2,…, Sn) that the system contains and the functions defined at the outset as being goals and interests of the organization in question (functions which we note as F1, F2,…, Fn).

2. Distribution of the *frequencies* of the various structures within the system. This involves measuring the system's statistical homogeneity.

3. Lastly, knowledge of the system's *internal constraints* considerably decreases complexity via the redundancy measuring these constraints.

We understand that, taken together, these three measurements represent an exploration of the culture of the organization considered, requiring work on formalizing the tacit knowledge and empirical adaptive practices the system has accumulated with the passage of time. In short, this involves exploring the system's degeneracy, namely the various strategies which have been put in place as alternatives to carrying out the company's operations and achieving its goals.

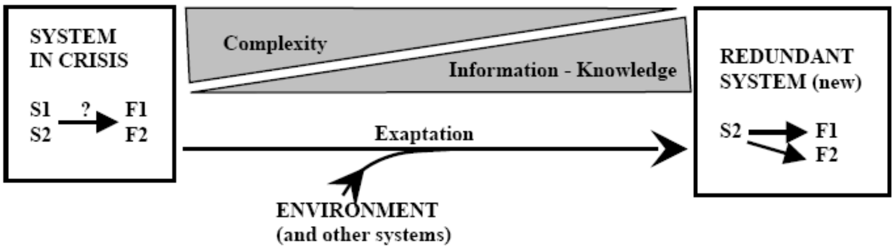

Fig. 2.

Exaptation now appears to us as the best way of describing this process of complexity reduction, accompanied by a return towards a redundant system. A crisis necessarily triggers a search for order and, considering the changing environment, it more specifically triggers a search for a new order. In other words, what's at stake the moment a crisis is solved is not structure diversification, but rather function diversification. However, as Edelman points out, various structures can carry out various functions in various contexts. Strictly speaking, this idea no longer corresponds to degeneracy, but rather to exaptation. Or one may understand this concept, introduced by Gould and Vrba [Gould and Vrba, 1982], as being equivalent to robustness, as described by Pavard et al. [Pavard, Dugdale, Bellamine-Ben Saoud, Darcy, Salembier, 2008, p. 127].

2.5 A global view of the complex system evolution model

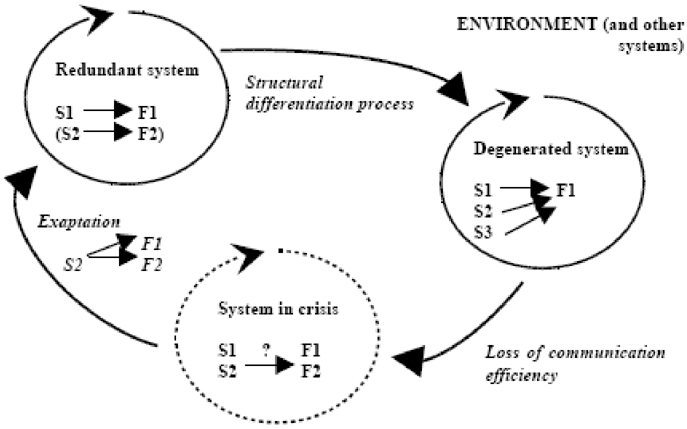

Fig. 3.

This global view represents the dynamics of the system evolution following the description given in previous paragraphs. Re is not an internal part of this evolution, but the external point of view which enables us to model it. Such a meta-reflection can contribute to reduce complexity by increasing knowledge on the global evolutionary process (being not reduced to situated action).

Note that the evolution of the system figured in our model will take a helicoidal shape. Such a spiral-form is the sign of real evolution of the system (different from progress).

3 THE ROLE OF RESILIENCE IN OUR MODEL.

Engineering always tries to reproduce an order and hence discern a system's invariance. In this way Re attempts to highlight the minimal characteristics of an organization's resilient behavior so as to measure its adaptation capacities and thus the organization's security level. In other words, its interest is reproducing resilience, and one might then talk about redundant resilience, once its goal is achieved.

However what we have sought to show is that resilience involves less a characteristic belonging to the system observed, than a characteristic of the observation itself and a participation in the system's evolution by means of that observation. Just like complexity, resilience is related to the viewpoint of someone wanting to know a system‘s dynamic. More specifically, resilience is precisely the result of searching for knowledge of a complex system. Thus, as we have seen, it also shares in reducing the complexity of the system measured.

We hope that our epistemological analysis of Re and our model will reveal an heuristic value and provide a new tool for practical researches. We finish our modest reflection by a quotation coming from Edelman and which formulates exactly our idea: “The contrast between degeneracy and redundancy at the structural level is sharpened by comparing design and selection in engineering and evolution, respectively. In engineering systems, logic prevails, and, for fail-safe operation, redundancy is built into design. This is not the case for biological systems.” [Edelman, 2001].

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