Robustness and resilience in the design of emergency management systems

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Summary

The aim of this paper is to propose a conceptual framework for the design of information systems for crisis management. The framework is grounded in the idea that the more an organisational system is unstructured (such as in a crisis situation), the more we need information technologies (IT) which are able to promote self organizing processes. In addition, IT systems should also help to improve the shared knowledge between stakeholders in order to promote a new form of organisation. Following this perspective, we will first give some examples showing that emergence and self organization are mandatory processes in the first phase in a crisis. We will also address the two notions of robustness and resilience in order to develop a more efficient approach in engineering crisis systems.

Introduction

Emergent processes can play a critical role in achieving robust socio-technical systems. This point will be illustrated in the following section using examples from emergency and crisis management. The ultimate goal of this paper is to propose a framework for designing robust socio-complex systems based on the idea of emergent and self-organised processes.

Regulation, emergence and self-organization in crisis management

The two examples in this section illustrate how complex systems use different kinds of regulation in order to maintain their performance or simply to survive. Two broad categories of regulation can be identified: functional and structural.

Of the two categories of regulation, functional regulation is the most common. The aim of functional regulation is to restore the initial functionality of the system. Classical engineering, cybernetics, and reliability engineering are mainly concerned with the concept of functional regulation. That is, when a perturbation arises in the environment, the regulation mechanism will return the system or its output to its default or expected value. Usually, the initial functionality of the system is maintained. However, there is no change to the internal structure of the system. A simple watt regulator or any regulation feedback mechanism exemplifies this first category of regulation.

When the external perturbation increases, more complex forms of regulation can be seen (structural regulation). Their aim is still to maintain the performance of the system, but the internal structure of the system may be changed. This change may be intentional, for example, it may be provoked by an actor within the system. Alternatively, the structural change may emerge in a 'non-intentional' sense. The following example shows the first case of this higher level of regulation.

Example 1: Structural regulation (self regulation) in a control room

When an air traffic situation becomes increasingly congested, the coordinator of the control room assesses the situation and may intentionally change not only the systems parameters, but its internal structure (organization). This is done in order to promote the potential ability of the system to handle the situation (Figure 1).

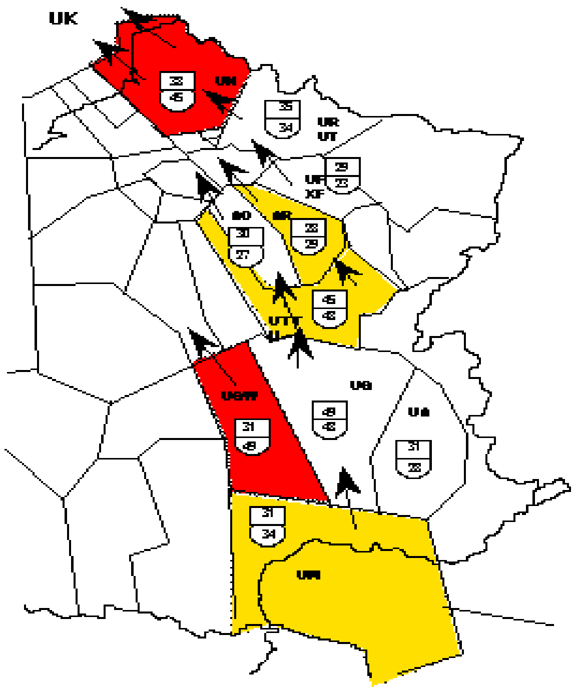

Fig. 1: *An example of structural regulation in Air Traffic Control (ATC). When some sectors (shown in red) are very busy because of the large number of aircraft, they may be subdivided by the ATC manager and assigned to new ATC controllers (from Salembier, 1994).*

In order to be efficient, the ATC manager should have a realistic overview of the situation (i.e. good data from all sectors, information on weather conditions such as wind perturbation, etc.) in order to take a rational decision.

With this type of regulation, it is important to note that the functional aim of the system is still maintained. In the example, the functional aim is to maintain the flow of air traffic and to avoid congestion.

In degraded or crisis situations it may not be possible to fulfill this aim. The manager no longer has a clear view of what is happening in the environment (i.e. there is a lack of information, or the information may be incorrect, etc.). As a consequence, the manager may not be able to make a rational decision. At this level of crisis, emergent and self organizing processes usually arise to restructure the system. In some cases, there may be no conservation of function (Salembier & Zouinar, 2002). That is, the emergent phenomena could change the local functionality of the sub-components.

The next example which concerns the Hurricane Katrina crisis in 2005 shows this concept. Here, emergence and self organization were the main systemic processes responsible for early recovery.

Example 2: Complex structural (or emergent) regulation during Hurricane Katrina

Soon after the arrival of the Hurricane Katrina, the communications infrastructure was destroyed, isolating the victims of the catastrophe and reducing the institutions' coordination capacities to zero (Comfort & Haase, 2006). Soon after, *non-institutional* actors[1] spontaneously started to restore communications using new technologies such as Wi-Fi networks and WiMAX. Their goal was to rebuild locally the communication links between the crisis sites and the external world. These efforts happened in spite of attempts by official organisations to limit the volunteers' involvement[2]. These spontaneous interventions are typical of self-organisation mechanisms which cannot be anticipated. (figure 2)

[1] For example, teams of people from large companies, private groups, etc.

[2] From 'Associated Press' (http://radioresponse.org/wordpress/?page_id=46) Mercury news, October 4, 2005 Mathew Fordhahl. *"The spontaneous wireless projects by groups that simply wanted to help -- government mandate or not -- is spurring interest in how to deploy the latest in communications technology and expertise in a more organized fashion after future disasters. Teams from large companies, private groups and the military converged on the Gulf Coast in ad hoc fashion to set up wireless networks, all the while battling bureaucracies that didn't seem to understand the agility and flexibility of the technologies being marshalled".*

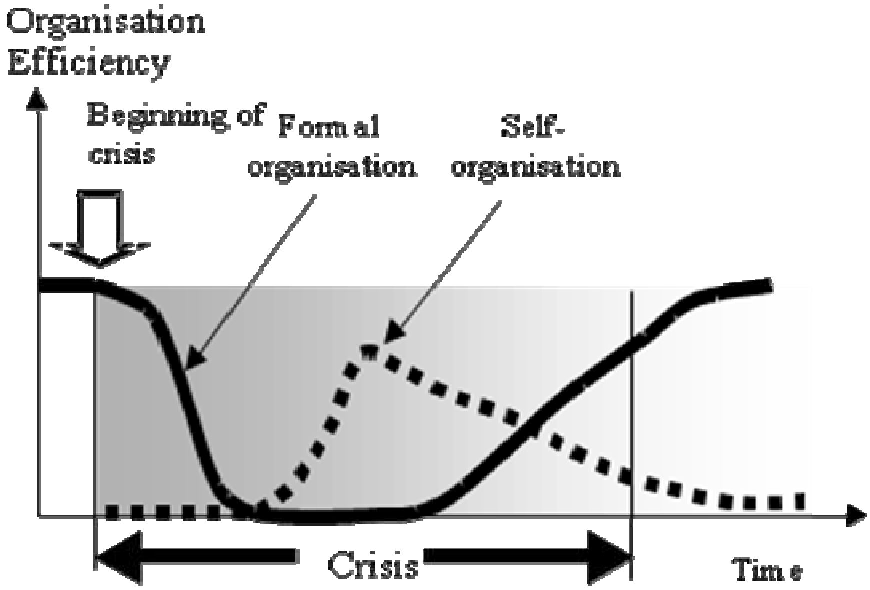

Figure 2: The dynamics of self-organization and institutional mechanisms in crisis situations: the case of Hurricane Katrina. The self-organization phenomenon (dotted curve) depicts the action of teams of volunteers who spontaneously tried to re-establish communications. The black continuous curve shows the evolution of the formal organization. Note that the amplitude of the curves and their development over time does not have an absolute value and is shown only to illustrate the positioning of the self-organization phenomena in crisis situations.

From these two examples, we can see that emergence is a mandatory mechanism for recovery when a socio technical system nears a crisis situation. If we consider designing emergency systems, it is useful to discriminate between the different types of regulations: a) functional, b) structural, c) structural and emergent or self organized.

The following section develops the idea that these three levels of regulation can be associated with different types of engineering. Resilient and robust engineering will also be reexamined in light of these three types of regulation.

From resilience to robustness engineering

Resilience engineering focuses on situations where it is possible to make reliable plans and where coordinators can anticipate the situation. The implicit hypothesis of this approach is that the organiser or the regulating system has a reliable model of the environment and that the functions for correcting any dysfunction do not deviate from what is expected.

Resilience engineering is based on the idea that it is always possible to maintain the functional organization, or at least part of it. Furthermore, it makes a clear distinction between the organization and the environment. In the case of a major crisis, these hypotheses cannot be maintained. In crisis situations the system no longer maintains a clear boundary between the organization and its environment. In addition we have the situation where the non-deterministic processes prevail over organized processes.

A resilient system generally aims to restore the initial functions of the system without fundamentally questioning its internal structure in charge of the regulation (Woods, 2005, 2006). Whilst it is true that in some situations the structure of the system may be intentionally modified, this modification is always undertaken within the context of a process where it is a supervising structure (i.e. the meta-structure) that decides the organisational changes.

The traditional approaches to reliability and security usually rely on resilient engineering. Engineers strive to return the system to its initial state maintaining its original functions.

From a system theory point of view, the processes linked to **robustness** are very different:

1) They inevitably do not guarantee that the function of the system will be maintained. Indeed, new functions can emerge. For example, a new organisation or new objectives for a company, etc.
2) It is difficult to disassociate the system from its environment since these two entities can be closely coupled.

Robustness has become a central issue in many scientific domains from computing to biology, through to ecology and finance (Bonabeau & al., 1996; Doyle & al., 2005; Kaufman, 1993; Lewontin & Goss, 2005; Walker & al., 1995). However, there is no globally agreed definition of robustness, and the situation is further blurred by its relationship to resilience and stability. Furthermore, according to how the term is used, very different theoretical or epistemological meanings may be attributed to the notion of robustness[3].

Following the distinctions made in this paper, the ergonomics of complex systems requires different types of engineering:

1) *Classical engineering* which is based on a functional approach in order to control simple regulation mechanisms.
2) *Resilience engineering* which deals with borderline and incidental situations, but which still remains within the framework of functional models and analytical approaches (e.g. stakeholders looking for ways to recover the initial situation).
3) *Robustness engineering* which refers to the behaviour of complex systems and distributed systems. Robustness engineering deals with non-deterministic processes such as those found in crisis situations. Only this approach lends itself to modelling and simulation of the self-organisation process and thus allows us to

3 For a detailed analysis of the concept of robustness in various scientific domains, see http://santafe.edu/sfi/research/robustness.php, http://discuss.santafe.edu/robustness, and Robust Design: a repertoire of biological and engineering case studies. Oxford University press (2005).

assess the role that technologies can play in this self-organisation.

Conclusion

The objective of this article was to clarify the concepts of robustness, resilience and regulation in the framework of the design of socio-technical complex systems. The hypothesis was that these concepts could only be clearly differentiated by considering their systemic properties. We have shown that resilience and robustness can be differentiated by the importance and dynamics of self-organised processes.

We also showed that self-organised processes are not the result of causal mechanisms controllable by an organisational structure. Instead, they result from distributed and non-deterministic processes. Robustness and resilience are complementary concepts because they cover two types of dynamics:

- A dynamic where it is still possible to anticipate or return the system to its initial state.
- A dynamic where the information flow is no longer compatible with any organised systems.

The true information is mainly local as a result of the crisis situation. In such situations, the interaction between the system and the environment is so strong (structural coupling) that it is no longer possible to maintain a clear distinction between them. At this stage, the system and the environment are driven by complex mechanisms such as self organisation, broadcasted information, within scale and cross scale interactions, etc. These mechanisms are in many ways unpredictable. However, they may generate new structures which are more able to cope with the new situation.

In this perspective, it is important to distinguish between resilience and robustness engineering for the design of complex situations. Resilience engineering has the objective of treating abnormal situations with traditional organisational tools (the search for functional stability, anticipation in degraded mode, etc.) and tries to look for *a posteriori* causality. For example, it often tries to assess the cause of a crisis by the derivation of a causal tree. Nevertheless, this analytical point of view is inappropriate in understanding crisis situations because of their unstructured characteristics.

References

Bonabeau, E., Theraulaz, G. & Deneubourg, J.L. (1996). Mathematical models of self-organizing hierarchies in animal societies. Bulletin of Mathematical Biology, 58: 661-717.

Comfort L.K. & Haase T.W. (2006). Communication, coherence and collective action : the impact of Hurricane Katrina on communications infrastructure. Public Works management & policy, Vol. 11, N°1, July 2006 1-16.

Doyle J.C., Low S.H., Paganini F., Vinnicombe G., Willinger W., Parrilo P. (2005) Robustness and the internet: theoretical foundations. Robust design. Editor: Erica Jen. Oxford University Press.

Kauffman, S.A. (1993). The origin of order: self-organisation and selection in evolution. New York: Oxford University Press.

Lewontin R.C., Goss P.J.E. (2005) Development, canalization, stochasticity and robustness. Robust design. Editor: Erica Jen. Oxford University Press.

Salembier, P. (1994). Assistance coopérative aux activités complexes: l'exemple de la régulation du trafic aérien. In B. Pavard (Ed.), Systèmes coopératifs: de la modélisation à la conception. Toulouse: Octares.

Salembier, P., & Zouinar, M. (2002). Air Traffic Management as a complex system: efficiency and reliability. Paper presented at the Complexity and Social Sciences -COSI, Summer School 2002, Chania, Crete, 30th June-6th July.

Walker B., Peterson G, Anderies J.M., Kinzig A. Carpenter S. (1995). Robustness in ecosystems. Robust design. Editor: Erica Jen. Oxford University Press.

Woods D. (2005) Creating foresight: Lessons for resilience from Columbia. In M. Farjoun and W.H. Starbuck (Eds), Organization at the limit. NASA and the Columbia disaster. Blackwell.

Woods D. (2006) Essential characteristics of resilience. In Hollnagel, E., Woods, D. D. & Leveson, N. (Eds.) (2006) Resilience engineering: Concepts and precepts. Aldershot, UK: Ashgate.