Design of robust socio-technical systems

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Summary

The aim of this paper is to propose a theoretical background in order to model the robustness of complex socio technical systems. We begin by clarifying the difference between robustness, resilience and regulation. We propose three categories of regulation: classic; structural; and emergent and self-organised. Using examples from our previous work, we show how emergent and self organised regulation can play a critical role in achieving robust socio technical systems. The ultimate goal of our work is to help design more robust socio-complex systems. To this end, we suggest that the ergonomics of complex systems implies different types of engineering: *classical engineering*, *resilience engineering*, and finally *robustness engineering*. The latter, being situated in distributed and complex systems theory, allows us to explain and manage the dynamic non-deterministic nature of robust socio complex systems. Using a multi-agent systems (MAS) approach we describe the development of a simulator of an emergency control room which can virtually assess the robustness of a new organisation in relationship to predetermined scenario.

Introduction

The objective of this paper is to tackle the question of how to design co-operative systems for emergency situations or for situations where there is a high degree of dysfunction. Such systems are described as 'robust' or 'resilient' by analogy with other technical devices facing the same difficulties.

Firstly, we clarify the distinction between resilience and robustness within the theoretical framework of complex systems, and in particular we analyse the complementarity of these two notions. We will then describe some socio cognitive mechanisms which participate in the concept of robustness.

From this perspective it is suggested that socio-technical complex systems which regularly operate in degraded mode evolve naturally in their organisation towards configurations which are increasingly able to respond to potential perturbations, rather than evolving towards better performance. We will show that the processes of self-organisation (which escape the formal organisation) are mainly responsible for the global robustness of the system. Furthermore, we also stress that it is necessary to take into account all of the levels of interaction, from the ‘weak’ interaction based on the informal coupling of the individual to the environment, to the structured social organisation (multi-level coupling) in order to understand the emergence of robustness. Finally, the paper is concluded by giving an example, in the area of the management of unforeseen situations, of a design which makes use of robustness criteria.

Robustness and regulation in complex systems

Robustness has become a central issue in many scientific domains from computing to biology, through to ecology and finance (Doyle & al., 2005; Bonabeau & al., 1996; 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[1].

Intuitively, a robust system is one which must be able to adapt its behaviour to unforeseen situations, such as a perturbation in the environment, or to internal dysfunctions in the organisation of the system, etc. However, this definition does not sufficiently discriminate between the notions of regulation or resilience which can also, to a certain extent, fit this definition.

The conceptual difference between these notions lies in the fact that a resilient system generally aims to maintain a constant output value, a performance, a production, or a function, etc. without fundamentally questioning the internal structure of the system in charge of the regulation. In certain cases, the structure of the system may be intentionally modified. However, this modification is always undertaken within the context of a process where it is a control structure (i.e. the meta structure) which decides the organisational changes.

From a systems theory point of view, the processes linked to robustness are very different since 1) they inevitably do not guarantee to maintain the function of the system’s components (new functions can emerge in the system) and 2) it is difficult to disassociate the system from its environment since the two entities can be so closely coupled.

In order to go forward in this distinction, we will consider three main categories of regulation.

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[1] For a more 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).

1) ‘**Classical**’ regulations have the objective of **constantly maintaining certain behavioural variables** of the system to one or more reference values. These regulations generally resort to ‘feedback’ type mechanisms which aim to ensure the stability of the system’s behaviour.

2) On a scale of increasing complexity, next are those regulations which, by **self-adaptation, modify the structure of the system itself.**

3) Finally, there is regulation by **emergence** and **self organisation**. In this case, the mechanisms that govern the system are no longer controlled by the stakeholders but result from decisions that are usually taken at a local level without any global vision of the situation.

The first two types of regulation assume the fact that 1) there is always a clear distinction between the system and the environment 2) the regulation aims to preserve the function of the system 3) the structural adjustments are intentional and are undertaken by a control structure which is capable of supervising all of the processes. Note that it is under these assumptions that the concept of resilience is often defined.

As an example, for McDonald, resilience represents ‘ the capacity of an organizational system to anticipate and manage risk effectively, through appropriate adaptation of its actions, systems and processes so as to ensure that its core functions are carried out in a stable and effective relationship with the environment’ (McDonald, 2006)

In the same book, and following the same point of view, Woods defines a resilient system as one which is able to monitor the boundary of its organization capability and which can adapt or adjust its current model (Woods, 2006, p.18). This point of view is very close to the definition of self adaptive systems in cybernetics (see beyond) and maintains the view that an agent or a structure is able to anticipate the unforeseen in an intelligent way. However, we note that this view does not cover the behavior of complex systems which are governed both by regular and non deterministic mechanisms (such as informal cooperation at the worker level) that the anticipative capabilities of observers or managers.
Following this point of view we stress that it is necessary to distinguish between resilient engineering that is concerned with the normal and the borderline’ capabilities of organization, and robustness engineering which is able to harness the more complex (and hidden) properties of self organized processes.

Examples of self organisation and emergence

As an example let us consider the case of Hurricane Katrina where non-institutional actors spontaneously intervened in the hours immediately following the destruction of the communication systems to rebuild locally the communication links between the crisis sites and the external world. This action was undertaken even though it met with resistance from some institutional actors who were opposed to actions out of their control (fig.1).

From the arrival of the hurricane, the communications infrastructure was destroyed, isolating the victims of the catastrophe and reducing the institutions coordination capacities to zero. At the same time, actors spontaneously started to restore the communications using new technologies such as Wifi networks and Wimax. This 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.

The conceptual frameworks used to study this type of mechanism do not agree well with those used in functional approaches. As we saw, 'classical' regulations assume the conservation of function (where the purpose of the regulation is to maintain the function of the system).

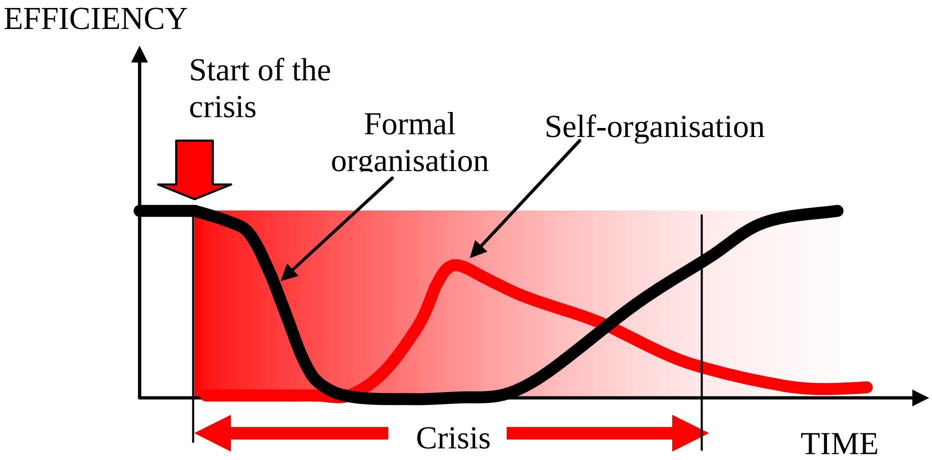

Fig. 1 *The dynamics of self-organisation and institutional mechanisms in crisis situations: the case of Hurricane Katrina. The self-organisation phenomena (grey curve) depicts the action of teams of volunteers who spontaneously tried to re-establish communications and who offered their help. The black curve shows the evolution of the formal organisation. 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-organisation phenomena in crisis situations.*

However, with self-organisation, it is difficult to speak of keeping the system's functions alive because, as in the previous example, crisis situations can lead to a readjustment of values, of the actors' interests and of their interaction with the

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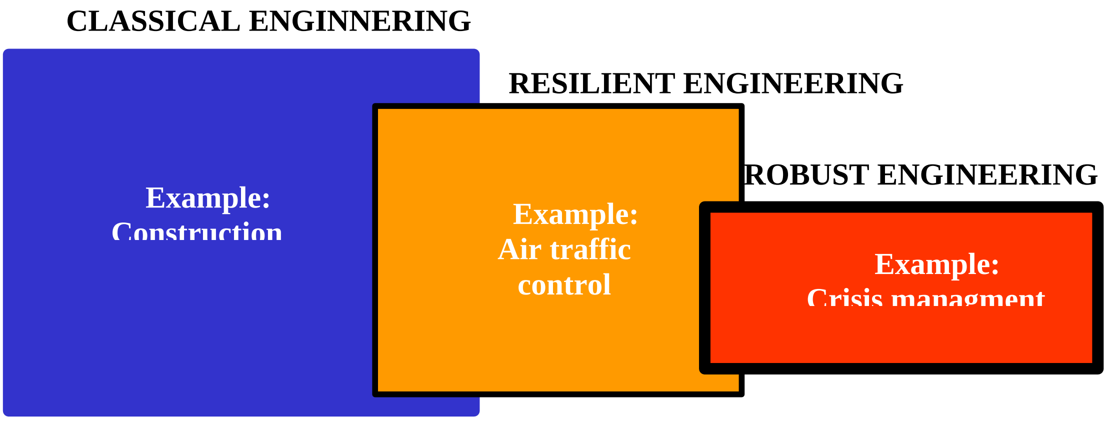
[2] From 'Associated Press' (http://radioresponse.org/wordpress/?page_id=46) Mercury news October 4, 2005 Mathew Fordhahl. *« The spontaneous wireless projects by groups that simply wanted to help -- government mandate or not -- is spurring interest in how to deploy the latest in communications technology 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 ».*

environment[3]. Therefore, the border between the system and the environment (which is at the base of the majority of traditional regulation models) is no longer clear; the links between these two entities are so strong that it is difficult to keep this distinction as the basis for an operational model.

Crisis Engineering

Following the point of view proposed in this paper, the ergonomics of the complex systems requires different types of engineering (fig. 2):

1) Classical engineering based on a functional approach in order to control the simple and structural 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 (stakeholders looks for a way 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 allows the modelling and simulation of the self-organisation process and thus allows us to assess the role that technologies can play in this self-organisation.



Characterized by:
- Functional stability
- Optimal performance
- Aim for ‘zero errors’
- Anticipation

Characterized by:
- Uncertain situation
- Reduced anticipation
- Dynamic reorganisation

Characterized by:
- Emergent functionalities
- No anticipation
- Self-organisation

Fig. 2: *Different types of engineering*

Resilience engineering focuses on situations where it is still possible to make reliable plans and where co-ordinators can still 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.

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[3] For example, in the domain of social insects

This point of view is based on the idea that it is always possible to keep alive the functional organisation (or part of it) and to keep a clear distinction between the organisation and the environment. In the case of crisis, these hypotheses cannot be maintained. In such situations we have a system where it is no longer possible to maintain a clear boundary between the organisation and its environment and where the non-deterministic processes prevail on organised processes. The self-organisation processes can result in an evolution of the systems functions as a whole. In the following part we provide two examples to demonstrate this aspect 1) an incident where the main functionalities of the system (Air Traffic Control) were maintained due to a non deterministic propagation of information of representational states (and without any central coordination) and 2) a normal coordination process (in an emergency control room) where the service provided to the community is made possible due to a self organised mechanism that is invisibile to the stakeholders.

In both cases, the flow of events that drive the situation could not be anticipated by any analytical approach, nevertheless, they are typical of regular complex situations. The point that we would like to make is that engineering such a situations requires tools and a methodology able to handle emergent or self organised processes (robust engineering).

Example 1 The emergence of a solution without self-organisation

Air Traffic Control: Example of emerging functionalities

This example shows how a simple broadcasting process is a basic mechanism for recovering from an unexpected situation. In this example, a particular type of plane (not a recent one) is in the approach phase for landing. In order to land, the pilot has to enter the beacon frequency of the instrument landing system (ILS) which keeps the plane on the correct course, into the his flight management system (FMS). This value which is given by the air traffic controller includes (on this occasion) two decimals. After many attempts the pilot cannot intercept the ILS and therefore cannot land. This situation results in a perturbation in the airspace close to the airport and in the en-route sectors which feed the approach area. During this time, and as an indirect effect, the information propagates throughout the system eventually reaching the flight crew of another plane stacked in the en-route control area, and who happen to know about the characteristics of the plane responsible for the perturbation. The diagnosis (it appears that the FMS of this type of plane does not accept two decimals) is retro-propagated along the network of agents to the controllers dealing with the approach sector who decide to use another flight path (with an associated frequency of only one decimal).

Example 2 Emergence of self organization in an emergency control room

This example concerns the cooperative mechanisms usually found in control rooms where people use face to face communications to regulate situations. It has been shown in such situations, that **mutual knowledge** is a key factor in understanding the efficiency of such organizations. Mutual knowledge is a perfect example of a self organized process because it emerges from local interactions. Furthermore, nobody is really aware of the ‘amount’ of mutual knowledge available at any time, or of the process by which mutual knowledge emerges. There are many cognitive processes related to the emergence of mutual knowledge, from explicit communications to implicit activities such as gesture and body posture, etc.

We have shown that in a real emergency control room, in order to cope with an overloaded situation, people are less aware of external cues (there is less overhearing for example) and are more focused on their personal activities. The result is that the amount of mutual knowledge in the group may drastically fall without people being aware of the situation.

In order to study this process and design more effective control room, a multi agent system was developed in order to model and simulate the local communication processes between the actors in the emergency room (Dugdale & al., 1999; Dugdale & al., 2000).

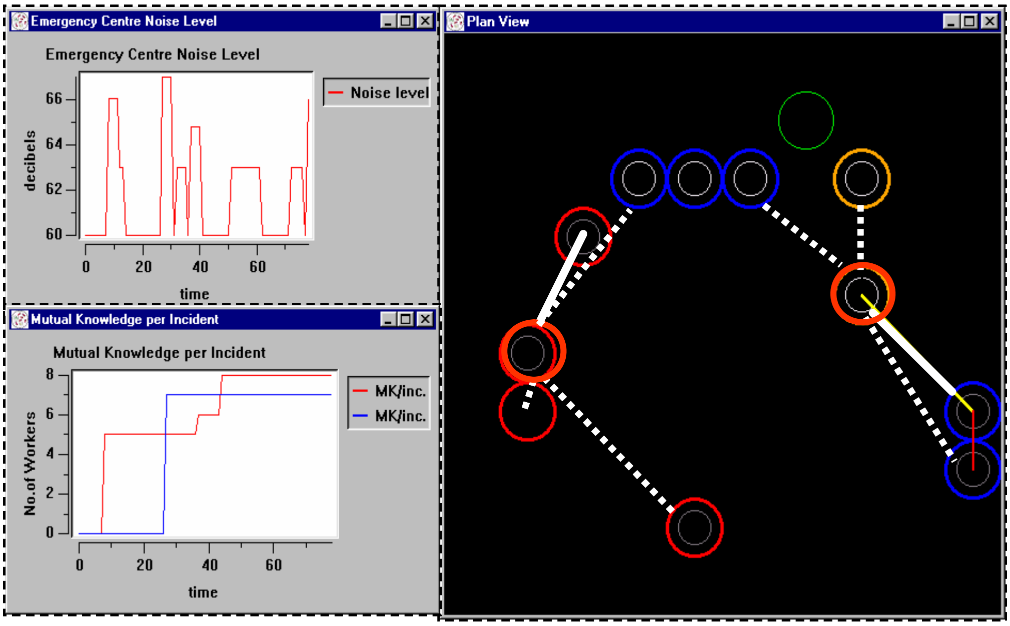

Fig. 3 *Right: This display shows the communications between actors (firemen: red circles, physicians: blue circles). The solid white lines refer to dyadic interactions between stakeholders, whilst the dotted lines show broadcasted information to the ratified listeners in the control room. Left: The upper graph shows the evolution over time of the noise level in the room. The lower graph illustrates the evolution of mutual knowledge over time.*

Part of the work focused on how information relating to emergency incidents was propagated throughout the room to the various actors. An extensive field study analysis identified the basic local communication acts between stakeholders (for example, the rules defining the exchange of information following an external telephone call or when searching for some information, the rules concerning the interaction between broadcasted information and the noise level in the room, and the rules governing the availability of actors as a function of the current activity, etc.).

By running the model we could analyse the relationship between the work organisation, the spatial organisation and the level of workload (from a normal situation to a crisis situation).

The simulations clearly showed that mutual knowledge (MK) may appear or disappear depending on many factors that cannot be controlled by the actors (Fig. 3). In situations where there is a high workload, MK does not emerge. This is mainly due to the fact that 1) the actors are no longer available to capture any broadcasted communications 2) the level of noise in the room may reduce the range of communication propagation.

Furthermore MK (being an emergent process) cannot be perceived at the level of the individual and thus the actors are unaware of the situation. After a while, the actors start to become aware of the fact that the whole system is no longer able to meet the external demand from callers (in effect, they receive negative feedback from external calls).

Interestingly, this example is typical of a good crisis organisation as it encompasses both formal and informal communication networks which are optimised to handle nominal as well as crisis situations. In this case, system robustness is achieved as the result of non deterministic processes (i.e. broadcasted communications between ratified and non ratified actors).

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. Our 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 a result of causal mechanisms controllable by an organisational structure, but that they result from distributed and non-deterministic processes (see Katrina example). Systems robustness comes from:

- The multitude of links between the different levels of the structure and environment, which cannot be controlled (Bressolle et al. 1996),
- The variety of the links: which may be strong, as when they result from the organisational structure, or weak and non-deterministic such as those resulting from broadcasting processes.
- The invariance of scale of the robustness mechanisms (robustness established at one or more levels of the systems stays compatible with the whole ecosystem which contains the socio-technical device)

In this perspective, we consider resilience engineering to be ‘classical’ engineering in that it has the objective of treating abnormal situations with traditional organisational tools (the search for functional stability, anticipation in degraded mode, etc.) and a search for *a posteriori* causality (causal tree, etc). This analytical point of view explains the theoretical difficulties encountered by this form of engineering in dealing with unforeseen situations, ‘normal’ accidents and the impossibility of anticipating them (Perrow, 1984; Greenfield, 2004). The approach proposed in this paper consists of using other conceptual tools, for example, complex systems theory, analysing cognitive and social activities to highlight strong and weak regulation loops, simulations to evaluate emergent processes, etc. This will allow us to put aside analytical approaches and design organisational and communicational devices that can be evaluated according to both their functional ability and their ability to produce sufficiently rich emergent behaviours to deal with unforeseen situations.

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