The contribution of complexity theory to the study of socio-technical cooperative systems

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1. Introduction

The objective of this paper is to analyse some of the conceptual and methodological contributions that complexity theory can make to the study of socio-technical cooperative systems. The theory of complex systems has developed along two complementary, but nevertheless distinct, axes. Chronologically, the first unifying concepts of the complexity paradigm resulted from the study of non-linear systems. Later, the study of distributed self organising systems made it possible to widen this initial approach to the analysis and modelling of social cognitive systems. The first school (non-linear systems) brought many conceptual and methodological contributions, however, these contributions are not directly applicable to the study of complex socio-technical systems, which are precisely the systems of interest to ergonomists and sociologists. On the contrary, the distributed approach, being interested in local interactions rather than structure and hierarchy, has found many applications fields ranging from the study of animal micro societies (ethology) to the study of human organisations on a social or cognitive level. Using examples from our analysis of human work activities, we will show how the concept of complexity can improve the methods of modelling and the design complex socio-technical systems. This paper concludes by trying to find an intermediate position between the analytical and complexity approaches which would allow us to understand real situations in better way.

2. Intuitive definition of a complex system

Whilst it is possible to give a precise definition of a complex system[1], we will provide a description in relation to our experience with the study of socio-technical systems.

[1] A system starts to have complex behaviours (non-predictability and emergence etc.) the moment it consists of parts interacting in a non-linear fashion.

A complex system is a system for which it is difficult, if not impossible to reduce the number of parameters or characterising variables without losing its essential global functional properties.

A truly complex system would be completely irreducible. This means that it would be impossible to derive a simplified model from this system (i.e. a representation simpler than reality) without losing all its relevant properties. However, in reality different levels of complexity obviously exist. Thus, the essential question is to know to what extent the properties of the socio-technical systems fall into one or the other of these situations.

The reduction of complexity is an essential stage in traditional scientific and experimental methodology (also known as analytic). After reducing the number of variables (deemed most relevant), this approach allows systems to be studied in a controlled way, i.e. with the necessary replication of results. This approach in itself need not be questioned. However, when considering complex socio-technical systems it is appropriate to analyse precisely the limits of the approach. The questions addressed in this article are: what are the theoretical and methodological limits of this traditional approach, and, what is the contribution of the distributed and complexity approaches? To illustrate our discussion we will use examples taken from an on-going study concerned with the redesign of an emergency call centre [Dugdale *et al*. 2000].

Four specific properties of complex systems will be discussed in relationship to their usefulness to socio-cognitive modelling:

Property 1: non-determinism. A complex system is fundamentally non-deterministic. It is impossible to anticipate precisely the behaviour of such systems even if we completely know the function of its constituents.

Property 2: limited functional decomposability. A complex system has a dynamic structure. It is therefore difficult, if not impossible, to study its properties by decomposing it into functionally stable parts. Its permanent interaction with its environment and its properties of self-organisation allow it to functionally restructure itself.

Property 3: distributed nature of information and representation. A complex system possesses properties comparable to distributed systems (in the connectionist sense), i.e. some of its functions cannot be precisely localised.

Property 4: emergence and self-organisation. A complex system comprises emergent properties which are not directly accessible (identifiable or anticipatory) from an understanding of its components.

3. Property 1: Non-determinism

Non-determinism of socio-cognitive processes is often considered as being due, either to a lack of knowledge of the observer about the analysed system, or to a disturbance of the system as a result of unforeseen causes (e.g. exterior events or noise etc.).

An analysis of the properties of complex socio-technical systems suggests that non-determinism can have an important functional role. We consider one of the most important mechanisms concerning cooperative systems: broadcasting [Rognin and Pavard 90]. We show that this mechanism is non-traceable (i.e. that it is difficult, if not impossible, to describe explicitly the information flows that are relevant in understanding how a collective functions) and that it provides a structure for the management of the memory of the collective. Figure 1 briefly explains how the broadcasting mechanism operates.

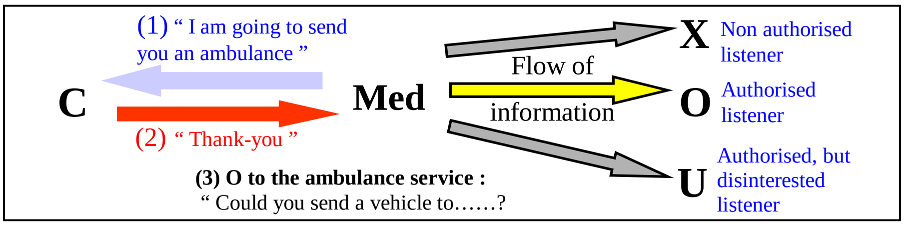

Figure 1. An example of the broadcasting mechanism. A caller, C, telephones a medic (Med) at the emergency centre to request an ambulance. This communication can be overheard by several people depending on their geographical position and the volume of the communication. These people can be either authorized, unauthorized, interested or disinterested interlocutors. In this example, agent O (in 3) overheard the conversation between the caller and the medic (1 and 2) because of his spatial proximity to the medic and the volume of the communication. As a result, agent O dispatched an ambulance without the medic making an explicit request.

Broadcasting is an important mechanism for understanding the efficiency of a collective in situations of co-presence (real or virtual). Indeed, it is the only mechanism which allows information sharing at a low cognitive cost. The classical theories of communication (mainly dyadic) have seldom analysed its functional role [Decortis and Pavard 94], although its cognitive components are described with precision [Goffman 87].

4. Property 2: Limited functional decomposibility

According to the traditional analytical approach, a system that is functionally decomposable is one whose global functioning can be completely deduced from knowledge of the function of its sub-components. A truly complex system cannot be represented by combining a collection of well defined functional components. A principal obstacle to the functional decomposability of complex systems is the dynamic and fluctuating character of their constituent functions. The interaction with the environment, as well as the learning and self organisation mechanisms makes it unrealistic to regard such systems as structurally stable.

An interesting property of socio-technical systems is their capacity to reorganise rapidly their functional structure. Depending on the context, agents may significantly modify the "rules of the game" and, for example, change their cooperative mechanisms. This change can occur without having been programmed at a central level. The example below, which describes a cooperative episode between several agents working in the same room, illustrates this type of mechanism. The episode is based on the broadcasting mechanism: a loudspeaker (held by a medic in white in the photograph) passes on the radio communications, transmitted by ambulances at the scene of accidents, to the rest of the collective (the personnel of the centre).

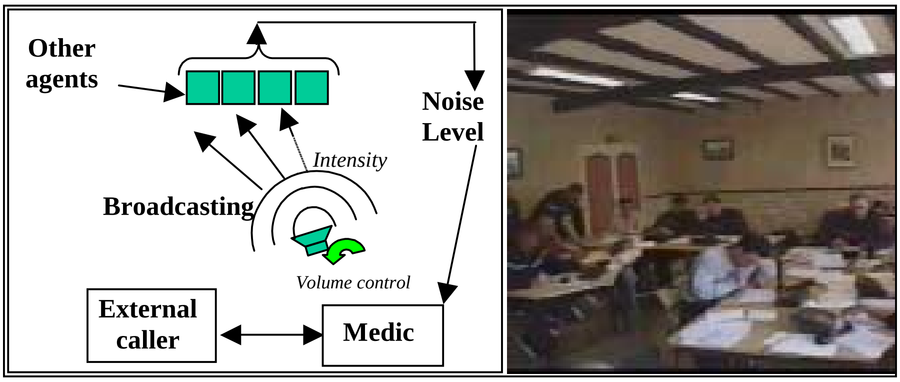

Figure 2. An example showing the flexibility of structural properties of a communication system. The mode of transmission of information between the agents depends on environmental factors (here, the ambient noise) and informal cognitive control exercised by individual agents (here, the estimated interest of the message to the collective). A medic changes the volume of the loudspeaker, depending on the semantic content of each message and the level of noise in the room. This allows him to adjust the scope of broadcasted message and optimise the way information is distributed to the collective.

We can see that the structural properties of a communication system (here, the mode of information distribution) depend on environmental factors and a semantic analysis of the content of the message. The example shows that the structure of the communication system, on which the efficiency of the collective depends, is subject to real time informal adjustment mechanisms. If this situation had been analysed according to the functionalist paradigm, the emphasis would have been on dyadic communications (e.g. the face to face and telephone communications between agents). Peripheral mechanisms (such as broadcasting and the ambient noise) would have been treated as more or less disturbing secondary events. However, these mechanisms are essential in order to understand the efficiency of the collective.

The functional importance of the broadcasting mechanism using the tuning of the loudspeaker volume has been simulated by computer in order to show the importance of regulating communications at the level of the collective [Dugdale and Pavard 2000]. A similar study in the field of air traffic control showed that it would be difficult to understand the reliability of this type of system without taking into account the numerous control loops which are due to informal sharing of information via radio messages and the concept of the 'floating ear' [Bressolle *et a*l. 96].

5. Property 3: The distributed character of information and representations

The notion of distributed information conveys different concepts. In its most commonly accepted meaning, a system is said to be distributed when its resources are physically or virtually distributed on various sites. The concept of distribution supports the concept of redundancy, when some distributed resources are redundant.

The notion of distributed representation also exists in the field of cognitive psychology [Zhang and Norman 94, Hutchins 90, Hutchins 95]. It covers the fact that, in the interaction between an actor and his environment, artefacts (tools) play an important functional role in the organisation of the reasoning and the transmission of knowledge. To illustrate this principle, we will take the example of paper strips in the domain of air traffic control. Paper strips are small pieces of paper on which aircraft characteristics, such as its call sign and its destination, are written. These strips help the controllers to represent information to themselves (for example by having the strips organised on the strip board according to the dynamic properties of the planes) and also to cooperate between themselves [Bressolle *et al*. 95]. Thus, we can speak about distributed representation, since some cognitive properties (such as memorizing and problem structuring etc.) are partially supported by artefacts in the environment. In one way, this notion is close to the concept of physically distributed systems.

Finally, we could introduce a third meaning to the notion of distributed systems which stems from connectionist models and conveys essential concepts for understanding the robustness of the collective in processing data. In the connectionist meaning, a distributed system is one where it is not possible to localise physically the information since it is more or less uniformly distributed between all of the objects (or actors) in the system (Figure 3).

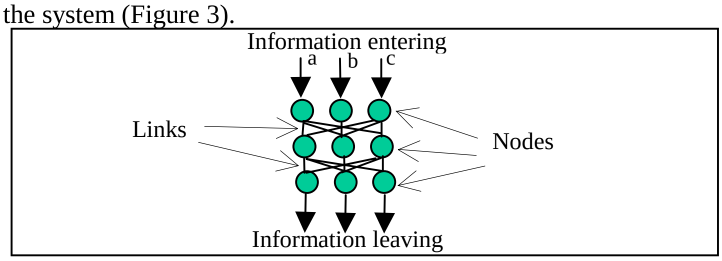

Figure 3. Diagram of a connectionist system (here a simple neural network). The information arriving in the system is distributed between a set of nodes (or neurons) as a function of the strength of each link. The strengths of the links are gradually adjusted using a learning mechanism which compares the actual behaviour of the network with the desired behaviour.

The learning mechanism ensures the distribution of the functional properties of the network (the property of recognition) between its neurons. If a network is forced to learn how to recognise shapes (or to associate actions with some conditions in the environment), the learning mechanism will distribute the information throughout all of the connections in the network. It will not be possible to attribute to any one of the connections a particular functional role. Such a network of distributed information offers some interesting characteristics of robustness and the ability to extrapolate answers to never seen situations. The term “distributed representation” is inappropriate here since it is impossible to identify any form of representation in such a network. The representation is “dissolved” either in the nodes of the system or in the links. Thus, a distributed system, in the connectionist sense, does not distinguish between concept, representation, and context, since these three entities are “encoded” simultaneously on the same support (nodes and links). We argue that a truly cooperative system works on both representational and connectionist modes. This is why the system is particularly robust in complex environments, which are unpredictable and non-deterministic.

The following example shows a situation encountered during our study of the emergency centre. Recall that the aim of the collective is to maximise cooperative behaviour between the actors, in order to respond in the best possible way to events in the environment (such as unexpected calls and work peaks, etc.). We showed in section 4 how the efficiency of this type of collective is based on a situation of co-presence which allows information to be distributed by broadcasting and "floating ear". Figure 4 represents this type of information distribution between agents and shows the importance of the interaction between the environmental factors (e.g. noise level and space constraints) and more central processes (such as the control of the modes of communication).

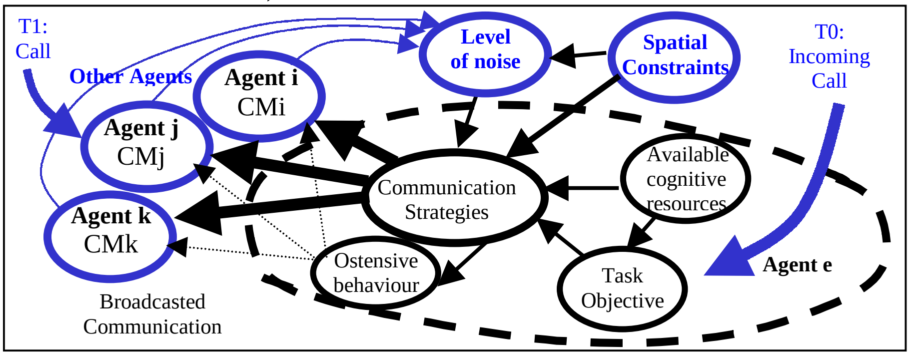

Figure 4: A diagram showing the distributed nature (in the connectionist sense) of cooperative systems. The diagram represents a collective composed of several agents (shown by circles: Agent i, j, k, etc.). At time T0, an incoming call is dealt with by agent e who adopts a communication strategy which aims to control the distributed character of the message. Verbal information (shown by thick black arrows) is distributed in a non-deterministic way (by broadcasting) to the other agents (Agents i, j, k) according to the characteristics of the environment: the noise level, the spatial constraints (the distance between the agents), the cognitive resources (workload) and other factors such as postural or gestural ostensive behaviour (shown by dotted arrows) which allows agents to control their listening behaviour [Benchekroun 94]. If at time T1, a call arrives which is related to a previous call, but is taken by an agent other than agent e, the collective (i.e. one of the other agents in the room) will be able to handle the call because of the common memory (CMi, CMj and CMk) established by the broadcasting mechanism.

We can see that a collective in a situation of co-presence, possesses characteristics which are comparable with those of a connectionist system. The information is distributed between the actors, with some redundancy, due to the broadcasting mechanism. Such a system can be regarded as complex because part of its functions cannot be reduced to a representation where it is possible to locate precisely a relevant piece of information. Neither the actors nor the observer can, at a given moment, give a deterministic plan of this process.

6. Property 4: Emergence and self organisation

Intuitively, a property is emergent when it can not be anticipated from knowing how the components of the system function. Emergence is not due to incomplete information regarding the components of the system, but to the non-linear and distributed character of the interactions. It consequently appears as if the system can, by its multiple local interactions, behave along some global features (emergent), which allow it to evolve towards more effective modes of organisation (self organisation) without calling upon exterior or interior structuring operations. If a system is capable of self organisation, its functions evolve over time so that they can respond better to the requests of its environment. In this sense, a complex self-organised system cannot be described as functionally stable.

Certain cognitive and communication processes in a collective correspond to this definition. We will give an example of an emergent process which is not beneficial since it does not produce a better functional structure, but instead produces a degraded behaviour, whose explanation escaped the analysis of participating actors [Benchekroun 94]. The difficulty occurred in the emergency centre during a period of intense telephone activity: a critical time where it is necessary to manage calls effectively. Paradoxically, it was also the time where the collective became dysfunctional, i.e. incapable of responding to an exterior request. An ergonomic analysis highlighted the importance of the interlocution and broadcasting mechanisms in the regulation of emergency calls: the agents were taking into account the ostensive behaviour of their colleagues in order to determine whether or not they could interrupt a busy colleague. Furthermore, the collective memory, which is constructed via broadcasting, was affected. The dysfunction was due to both the unavailability of agents and the fact that as the workload rose, agents became increasingly unable to acquire information from their colleagues via the ‘floating ear’. It is thus a purely local interaction between agents linked with the distribution of information mechanisms that produced a global (emergent) behaviour. Formally modelling this process allowed us to confirm the relevance of this interaction between local behaviour and environmental factors [Pavard et al. 90].

7. Conclusion: a paradigm for the analysis of complex socio-technical systems?

This paper explored the usefulness of the complexity paradigm in analysing socio-technical cooperative systems. We defined and analysed four characteristics of complex systems which were illustrated using examples taken from our work in designing cooperative systems in the domains of air traffic control and emergency control centres. We demonstrated that these four characteristics, which are not treated within the framework of classical analytical approaches, are essential to understand certain functional aspects of cooperative work. For example, we identified the functional role of the broadcasting mechanism as being at the heart of the distribution of information between agents in a socio-technical system. By utilising complexity theory we can identify that the mechanism is non-traceable and non-deterministic. Furthermore, by identifying the distributed nature of this mechanism we can hypothesise that the robustness of the overall system, i.e. the capacity of the system to handle unforeseen data, is functionally related to the concept of a locally distributed control of information. These mechanisms are principally concerned with local interactions (between social actors) and are not represented at a central organisational level where certain functional properties (e.g. reliability, robustness, or the occasional abnormal operation of the collective) emerge.

This approach and the results would be incomplete if we could not prove them in a productive way, i.e. by simulating the effect of local interactions on the global collective decision. This stage must permit the emergence of global properties of system robustness. Several simulations are currently being analysed to demonstrate the power of this approach [Dugdale *et al*. 2000, Salembier and Zouinar 2000].

From a general standpoint, we defend the idea of a complementary structural and distributed (also termed 'dynamic') approach both in cognitive science and more generally in social science. These two approaches cover two important dimensions in our understanding of the collective. Used alone, no approach is sufficient to explain the robustness and dynamic nature of socio-technical systems [Mitchell 99]. The classical analytical reductionist approach is particularly weak in explaining the emergence of functional properties, despite the fact that in socio-technical complex systems, the strength of the collective lies in such properties.

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