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Boundaries, Hierarchies and Networks in Complex Systems

PAUL CILLIERS

Department of Philosophy
University of Stellenbosch
Stellenbosch7600
South Africa

Fpc@akad.sun.ac.za

Abstract

Models used in the understanding of complex entities, like organisations, are problematic in several respects. After an introductory discussion of this problem, this paper addresses the problems associated with the boundaries of complex systems, arguing that although boundaries do exist, they have a peculiar nature. Similarly, it is argued that although hierarchies form an important part of the structure of complex systems, they are not clearly defined or "nested" as is often assumed. Hierarchies should also in principle be transformable in a viable system. Finally, the usefulness of network models are investigated. The conclusion is that although network models have a structure similar to that of complex systems, they are subject to the same limitations all models of complexity are faced with. A few implications for our understanding of organisations are mentioned.

Keywords: Complexity, hierarchies, boundaries, modelling, networks, organisations

Complexity

Complexity theory has been a bright new star in the academic firmament for a while now. It is being pursued eagerly in a number of disciplines (see Thrift 1999), generally with a fair amount of hype. Why the enthusiasm, and more particularly, why is there so much of it in the organisational sciences? My suspicion is that the reason has a lot to do with the hope that we are finally onto a method that will improve our understanding of, and therefore our control over complex systems like organisations. The argument may go like this: if we pay enough attention to flat hierarchies, networks of interaction, non-linearity and emergence, we may finally be able to develop a general theory of complex organisations. This will, of course, be a much sought after management tool, and it should come as no surprise that so many are looking for it. It should also not be a mystery that the Santa Fe style of approaching the problem – lots of chaos theory and mathematics – should be the most popular. We want to predict the behaviour of complex systems, and for that we need good models.

Of course complexity theory did not appear on the scene without antecedents. In many ways it is a continuation of what was done in cybernetics, general systems theory and chaos theory. These disciplines also generated lots of hype – and lots of results, of course – but could never quite deliver the theories and tools required for a general theory of complexity. There are a number of reasons for this, but two related reasons, I think, are central: they did not pay enough attention to the historical nature of complex systems, and consequently, did not pay enough attention to the radically contingent nature of a complex system. Complexity was taken to be symmetrical in time, a point of view no longer tenable after the work of Prigogine. (See also Dasgupta 1997: 138, and Emmeche 1997: 48, 58).

The burning question is whether we can take this and other characteristics of complexity (Cilliers 1998: 2 – 7) into account, and then succeed where previous efforts failed? Is it possible to have a general theory of complex systems? In this paper I suggest that although we can say a lot of important things about complexity in general, it is not possible to develop a general model for complex systems. This has to do with the meaning of the notions "model" and "complexity". In what follows I will look at the limitations of models of complex systems by examining the status of boundaries and hierarchies. I will conclude by reflecting on the status of neural network models, and on some of the implications the whole argument has for our understanding of organisations.

There is one question that can be pre-empted now: is it possible to have a *science* of complexity? I would argue that it is, but that it implies a revision of our notion of what constitutes science. In an editor's note to a short review article by Corning (1998) the following statement is made: "Until the 'complexity science' researchers can develop a formal notation in symbols and syntax, while at the same time respecting its subjective nature [sic], it will not really be a 'science' " (197). If this strict, formal and quantificatory attitude remains the way in which science is defined, then there will be no "science" of complexity. However, our knowledge of complex systems is, to my mind at least, undermining such a strict understanding of science. It forces us to consider strategies from both the human and the natural sciences, to incorporate both narratives and mathematics – not in order to see which one is best, but in order to help us to explore the advantages and limitations of all of them.

> Complexity studies should thus be seen not as aiming at a new "synthetic theory" of complexity of any kind, but as a cross-disciplinary field of research and meeting place for dialogue between specialised groups of people such as biologists, physicists, philosophers, mathematicians, computer scientists, and, last but not least, science writers.
>
> (Emmeche 1997: 43)

Before turning to how boundaries and hierarchies make the limitations of our models of complexity explicit, we should first explore the notion of a model in a little more detail.

Models

The notion of a model is central to scientific understanding. The notion will be used here in a wide sense (i.e. theories and systems of rules can also be seen as models). In the context of complexity, the role of models is described in the following way by Csányi (in Khalil and Boulding 1996: 148):

> Any kind of scientific statement, concept, law, and any description of a phenomenon is a model construction which tries to reflect phenomena of the external world. Reality is extremely complex; it consists of strongly or more weakly related events. Science makes an attempt to separate and isolate different effects and phenomena. It seeks the simplest relationships by which examined phenomena can at least be described or demonstrated. It creates simplified models which only partly reflect reality, but which allow contemplation, and what is most important, pragmatic, even if sometimes modest, predictions.

We cannot deal with reality in all its complexity. Our models have to reduce this complexity in order to generate some understanding. In the process something is obviously lost. If we have a good model, we would hope that that which is left out is unimportant. It should be clear already that purely quantitative models of complex systems, which abstract from a set of real properties to numerical values, will be problematic (Emmeche 1997: 54). The underlying problem with models of complexity is, however, even more serious. No matter how we construct the model, it will be flawed, and what is more, we do not know in which way it is flawed.

In order to understand this claim we have to remember the non-linear nature of the interactions in complex systems. This non-linearity has two important consequences. In the first place, when there are a lot of simultaneous, non-linear interactions, it soon becomes impossible to keep track of causal relationships between components. Secondly, from the non-linear nature of complex systems we can deduce that they are incompressible (Cilliers 1998: 10). If we add to this the historical nature of complex systems, the problem should become clear: Models have to reduce the complexity of the phenomena being described, they have to leave something out. However, we have no way of predicting the importance of that which is not considered. In a non-linear world where we cannot track a clear causal chain, something that may appear to be unimportant now, may turn out to be vitally important later. Or *vice versa*, of course. Our models have to "frame" the problem in a certain way, and this framing will inevitably introduce distortions[1].

This is not an argument against the construction of models. We have no choice but to make models if we want to understand the world. It is just an argument that models of complex systems will always be flawed in principle, and that we have to acknowledge these limitations.

What then of the argument that it may be possible to incorporate absolutely all the information concerning a complex system into some fancy (neural network) model? I do not wish to argue that it is impossible to repeat the complexity of a system in another medium, but one should remember that we now have a "model" that is as complex as the system being modelled. It will be as difficult to understand as the system itself, and its behaviour will be as unpredictable. If the history of the model and the history of the system is not kept identical (and I cannot see how this can be done in anything but the most trivial of cases), the two will soon become uncorrelated. My conclusion is that it is impossible to have a perfect model of a complex system. This is not because of some inadequacy in our modelling techniques, but a result of the meaning of the notions "model" and "complex". There will always be a gap between the two. This gap should serve as a creative impulse that continually challenges us to transform our models, not as a reason to give up.

Structure

The claim that our models of complex systems cannot be perfect introduces a next layer of problems: what is it then that is described by our models? Are they merely constructions or instruments, or do they reflect reality in some way? Both claims have had strong support. One way of naming these two traditions is to say that the attempt to reflect nature (accurately) is a modern approach, and that giving up that attempt is post-modern. Emmeche (1997: 46) argues that we can only deal with complexity if we adopt elements from both kinds of ethos. One can

[1] In this paper the ethical issues arising from the acknowledgement of complexity will not be examined, but it should be clear that the selection of a certain frame always involves normative issues. (See Cilliers: 2000b.)

make a slightly stronger, and more difficult demand: both approaches should be followed simultaneously. We are always busy with the world itself, and simultaneously, we cannot grasp it fully. Let us explore this a little further.

A distinction is often made between "descriptive" and "ontological" complexity (e.g. by Emmeche 1996: 43). The first has to do with the complexity of our descriptions, the second with the "actual" complexity of things in the world. If one maintains this distinction, it would be easy to fall into the kind of dichotomy mentioned above. We would have descriptions of the world, and separate from it, the world itself. This is the trap stepped into by the classical approach to artificial intelligence: trying to make formal models that should represent the world accurately (see Cilliers 1998: 58 – 88). The relationship between our descriptions of the world and the world itself is, however, more complex. There is a constant to and fro between them in which our models and, especially in the case of the human sciences, the world itself is transformed. Since our models cannot "fit" the world exactly, there are many degrees of freedom in which they can move. They are, however, simultaneously constrained by the world in many ways. There is feedback from the world that tells us something about the appropriateness of our models. The situation is the following: there is on the one hand freedom in modelling, and on the other hand, constraints from reality, but the two are not independent from each other.

We will return to the notion of constraints below when we look at boundaries, but for now it is important to realise that the notion of a constraint is not a negative one. It is not something which merely limits possibilities, constraints are also *enabling*. By eliminating certain possibilities, others are introduced. Constraints provide a framework that enables descriptions to be built up around it[2]. When dealing with complexity, though, these frameworks cannot be fixed. They are constantly being transformed, and therefore our models will always be provisional.

What then is it that is described by our models? I would argue that models attempt to grasp the *structure* of complex systems. Complex systems are neither homogenous, nor chaotic. They have structure, embodied in the patterns of interactions between the components[3]. Some of these structures can be stable and long lived (and are therefore easier to catch in or models), whilst others can be volatile and ephemeral. These structures are also intertwined in a complex way. We find structure on all scales[4]. In order to see how difficult it is to grasp these structures, it is necessary to look at the boundaries of complex systems, and to the role of hierarchies within them.

Boundaries

In order to be recognisable as such, a system must be bounded in some way. However, as soon as one tries to be specific about the boundaries of a system, a number of difficulties

[2] For a more detailed discussion of constraints, see Juarrero (1999: 131 – 150).
[3] The notion of "structure" is used in many different and confusing ways. In this analysis it refers to the patterns of interaction in the system, and underplays a distinction between the structure on the one hand, and activities within that structure on the other. Structure is the *result* of action in the system, not something that has to exist in an *a priori* fashion. The advantages of a network model of complexity is that we can depict rather stable structures, as well as more volatile ones using the same means (see Cilliers 1998: 99 – 100).
[4] Structure is not chaotic, but often has a fractal nature (Csányi in Khalil and Boulding 1996: 158), especially if the system is critically organised (see Cilliers 1998: 96 – 98).

become apparent. For example, it seems uncontroversial to claim that one has to be able to recognise what belongs to a specific system, and what does not. But complex systems are open systems where the relationships amongst the components of the system are usually more important than the components themselves. Since there are also relationships with the environment, specifying clearly where a boundary could be, is not obvious.

One way of dealing with the problem of boundaries is to introduce the notion of "operational closure"[5]. For a system to maintain its identity, it must reproduce itself (internally). These arguments often follow from the work by Maturana and Varela on autopoiesis. Zeleny (in Khalil and Boulding 1996: 123) defines an autopoietic system as

> ... a system that is generated through a closed organisation of production processes such that the same organisation of processes is regenerated through the interaction of its own products (components), and a boundary emerges as a result of the same constitutive processes.

When dealing with complex systems in an "operational" way, there is nothing wrong with this approach. One should be careful, however, not to overemphasise the closure of the boundary. The boundary of a complex system is not clearly defined once it has "emerged". Boundaries are simultaneously a function of the activity of the system itself, and a product of the strategy of description involved. In other words, we frame the system by describing it in a certain way (for a certain reason), but we are constrained in where the frame can be drawn. The boundary of the system is therefore neither purely a function of our description, nor is it a purely natural thing. We can never be sure that we have "found" or "defined" it clearly, and therefore the closure of the system is not something that can be described objectively. An overemphasis on closure will also lead to an understanding of the system that may underplay the role of the environment. However, we can certainly not do away with the notion of a boundary.

Our understanding of boundaries can be given a little more content by considering the following two issues. The first concerns the "nature" of boundaries. We often fall into the trap of thinking of a boundary as something that separates one thing from another. We should rather think of a boundary as something that *constitutes* that which is bounded. This shift will help us to see the boundary as something enabling, rather than as confining. To quote Zeleny (133) again:

> All social systems, and thus all living systems, create, maintain, and degrade their own boundaries. These boundaries do not separate but intimately connect the system with its environment. They do not have to be just physical or topological, but are primarily functional, behavioral, and communicational. They are not "perimeters" but functional constitutive components of a given system.

As an example of this logic, think of the eardrum. It forms the boundary between the inner and the outer ear, but at the same time it exists in order to let the sound waves through. As a matter of fact, if it was not there, the sound waves would not be able to get through at all! If the boundary is seen as an interface participating in constituting the system, we will be more concerned with the margins of the system, and perhaps less with what appears to be central[6].

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[5] The work of Niklas Luhmann provides a good example of this approach. (For a monograph in English, see Luhmann 1989.)

[6] Although it will not be elaborated on in this text, a number of the ideas presented have a close affinity to arguments from deconstruction. For more detail, see Cilliers 1998, especially chapter three.

A second boundary issue concerns the "place" of the boundary. The propensity we have towards visual metaphors inclines us to think in spatial terms. A system is therefore often visualised as something contiguous in space. This tendency is reinforced by the prevalence of biological examples of complex systems. We think of systems in an "organistic" way. Social systems are obviously not limited in the same way. Parts of the system may exist in totally different spatial locations. The connections between different components could be seen as virtual, and therefore the system itself may exist in a virtual space. This much should be self-evident to most inhabitants of the global village, but there are two important implications to drawn from this. The first is that non-contiguous sub-systems could be part of many different systems simultaneously. This would mean that different systems interpenetrate each other, that they share internal organs. How does one talk of the boundary of the system under these conditions? A second implication of letting go of a spatial understanding of boundaries would be that in a critically organised system we are never far away from the boundary. If the components of the system are richly interconnected, there will always be a short route from any component to the "outside" of the system. There is thus no safe "inside" of the system, the boundary is folded in, or perhaps, the system consists of boundaries only. Everything is always interacting and interfacing with others and with the environment; the notions of "inside" and "outside" are never simple or uncontested.

In accepting the complexity of the boundaries of complex systems, we are committed to be critical about how we use the notion since it affects our understanding of such systems, and influences the way in which we deal with them. The notion of "boundary critique" is not a new one (see Midgley *et al*: 1998), but in this critique we have to keep the enabling nature boundaries as well as their "displacement" in mind.

Hierarchies

An analysis of the importance of hierarchies has been part of the study of complex systems for a long time (Simon 1962, Pattee 1973). In his seminal paper Simon gives at least three reasons why hierarchies are important. In the first place, a modular structure would make it easier for new complex systems to be generated. He uses the example of two watchmakers, one building each watch from scratch, the other first constructing basic subassemblies, and then connecting these together. The second, he argues, will be more efficient. This "hierarchical" structure would also allow the system to take better advantage of evolutionary opportunities. In the second place, hierarchies establish unambiguous routes of communication. If the system is hierarchical, an algorithm can be developed that would ensure that information would get from A to B. In the third place Simon argues that hierarchical systems have a lot of redundancy, and that it is therefore possible to construct models of such systems that are simpler than the system itself (a claim which is obviously somewhat at odds with the position argued for here).

A somewhat contrary position is taken in some contemporary discussions of complex systems. A lot of emphasis is placed on self-organisation and the "distributed" nature of the structure in a system. According to these arguments, complex systems do not have central control systems. They have to be dynamic and adaptable, not rigid or invariable. Consequently the notion of hierarchy is resisted. In terms of the structure of organisations, it is often argued that to the extent that there should be hierarchies at all, they should be shallow and loose. There must be enough space for innovation.

Both these positions oversimplify the role of hierarchies in complex systems. Hierarchies are certainly necessary, but the way in which they work differs in important respects from the classical understanding. Let us examine these differences.

In the first place it must be underscored that systems cannot do without hierarchies. Complex systems are not homogeneous things. They have structure, and moreover, this structure is asymmetrical (see Cilliers 1998: 120, 124, 147–148). There are subsections with functions, and for them to exist at all there has to be some form of hierarchy. Problems arise, however, when these hierarchies are seen as either too clearly defined, or too permanent. The classical understanding of hierarchies tends to view them as being nested[7]. In reality however, hierarchies are not that well-structured. They interpenetrate each other, i.e. there are relationships which cut across different hierarchies. These interpenetrations may be fairly limited, or so extensive that it becomes difficult to typify the hierarchy accurately in terms of prime and subordinate parts. Simon (1962), of course, knows this. Nevertheless, in the hope of coming up with enough hierarchical structure to enable modelling of the system, he emphasises that which falls within the hierarchies, and not the interpenetrations. He argues that many complex systems are “near decomposable”, meaning that hierarchical models will provide a fair approximation. This view would see the interpenetrations as part of the messiness of complexity, whereas I would rather see them as indispensable. Similar to the notion of boundaries discussed above, the structure of a complex system cannot be described merely in terms of clearly defined hierarchies. This is because the structure of complexity is usually fractal, there is structure on all scales. The cross-communications between hierarchies are not accidental, but part of the adaptability of the system. Alternative routes of communication are vital in order to subvert hierarchies that may have become too dominant or obsolete. Cross connections may appear to be dormant for long, but in the right context may suddenly play a vital role.

This leads directly to the next point: part of the vitality of a system lies in its ability to transform hierarchies. Although hierarchies are necessary in order to generate frameworks of meaning in the system, they cannot remain unchanged. As the context changes, so must the hierarchies. Some hierarchies may be more long-lived than others, but it is important to perceive of hierarchies as transformable entities. This may seem to be self-evident, but I do not think that managers regularly think in these terms. They may realise that they can be replaced, but they do not often perceive their positions to be in principle provisional. They also tend to think of the interpenetrations as obstacles to efficient management, and not as vital routes of communication.

To summarise then, hierarchies are necessary, but they are not neatly nested. The hierarchies in a system have a complex structure themselves. Whatever their structure, hierarchies are furthermore not permanent, they have to be transformed. Transformation does not imply that hierarchies are to be destroyed, but that they should be shifted[8]. The argument is thus not setting up an opposition between, for example, hierarchies and teams in an organisation, and then insisting that one should find a balance between the two (see e.g. Romme 1996). Teams have hierarchies too, and this should be acknowledged. It is better to make as much as possible of the structure in an organisation explicit, and then to deconstruct it, rather than to claim that there is no (or little) hierarchical structure, denying (and thereby actually affirming) the implicit structures that have to exist. The first option also makes the lines of responsibility

[7] This is perhaps again a legacy of biological models – subsystems are seen as “organs”. Biological systems are subjected to constraints that may not apply to all complex systems, especially not social systems.

[8] This claim can also be substantiated by arguments from deconstruction. See footnote five.

within the organisation more explicit, and therefore it should not only lead to a more efficient organisation, but also to a more ethical one (see Cilliers 2000a).

Network Models

A final issue to consider briefly is the role of network models in understanding complex systems. Do they have any advantages? I have argued previously (Cilliers 1998: 18 – 21) that neural networks provide a better framework for modelling complex systems than rule-based models. This claim needs to be qualified. The argument that network models mimic the kind of structure found in complex systems is still, I feel, a sound one. Network models can self-organise, information is represented in a distributed fashion, and most importantly, structures which are very loose, very rigid, and everything in between can be implemented in the same medium. The qualification, however, lies in the difference between the notions “mimic” and “model”. Despite a huge amount of practical problems (for example in the training of recurrent networks), it is in principle possible that a neural network can simulate a complex system, but I do not think that the problem of modelling complex systems discussed at the beginning of this paper can really be circumvented.

Why not? Although the training of neural nets involves a process where the network is allowed to develop structure without using a pre-existent theory of how it is done, a theoretical framework is nonetheless introduced. This has only a little to do with the selection of the type of network and the training algorithm, but a lot to do with the selection of the *data* presented to the network. We cannot present the network in training with life, the universe and everything; we have to select. That means that a framework defining the boundary of what is in and what is out, what is important and what is marginal, has to be decided upon before training commences. This does not mean that we cannot generate some very useful network models. It just means that these models will have some *a priori* constraints which will have to form part of the interpretation of the results. In that respect neural networks should not be treated in a different way to any other model. There is a rather serious problem, however. Given its distributed nature, the capabilities and limitations of the model is not available in an explicit fashion. We present the network with new data, and then we have to trust the result – unless the network was “engineered” in such a way that we know what it does. In such a case, however, a model of the system would have had to exist beforehand in order to make the engineering possible. It is sometimes better to work with a simple model where the limitations are explicit than to work with a complex model that may turn out to be a false friend.

Conclusions

Let me conclude with a few summary remarks highlighting the implications of the arguments presented for a theory of organisations.

1. Complexity theory increases our understanding of complex systems like organisations, but it does not present us with tools which can predict or control the behaviour of a specific organisation accurately. We may be able to learn a lot about the kind of dynamics involved in the functioning of such systems, but we will not be able to use these general principles to make accurate predictions in individual cases. Complexity theory underscores the importance of contingent factors, of considering the specific conditions in

a specific context at a specific time. No general model can capture these singularities. Although we cannot escape the use of models, we can also not escape the responsibility involved in using them – a responsibility that can never be shifted onto the models themselves.

2. Organisations do have boundaries, and these boundaries play an important role in determining the identity of the organisation. However, boundaries are not clearly defined in their nature or their place. The vitality of an organisation will be improved if we do not try too hard to define or fix its boundaries, but allow for their constant renegotiation.

3. Since organisations do have structure, they inevitably also have hierarchies. We will not understand the organisation if we do not allow for the role of these hierarchies, but we have to remember that they are often not clearly determined and that they interpenetrate. We have to allow for the important role that could be played by apparently marginal elements, that is, we have to remember that the hierarchies themselves have a complex structure. In a vital organisation it will be possible to transform existing hierarchies into different ones, but not to eliminate them.

A final word can be added concerning the identity of an organisation. It may appear from these arguments that such a notion will be difficult to maintain. I think not. The identity of an organisation cannot be static, but neither should it be too fluid. It emerges exactly from the way in which the boundaries and the hierarchies of that organisation are simultaneously maintained and transformed.

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