On the Role of Self-Organisation as a Model for Networked Systems

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Abstract. In this paper, the role of the concept of self-organisation as a model in the analysis and design of advanced networked systems is investigated. In a first step, criteria for the definition of scientific models and their explanatory roles are introduced on the background of theories of models in the philosophy of science: intended scope, selection of the properties modelled, type of analogy, and levels of formalisation, abstraction and idealisation. In a second step, the applicability of these criteria to model-building in engineering is discussed, in order to assess some of the implications and limitations of modelling networked systems as self-organised systems, with particular attention to the role of the systems' environments in these models.

1 Introduction

It has become a common practice in computer science and related fields to invoke the functional and organisational principles of natural systems, such as organisms, populations or ecosystems, as models for the analysis and design of technological artefacts. Those natural systems are adapted to their respective environments by way of processes of random variation and natural selection; and they are adaptive to variations in these conditions by virtue of their self-organising properties, in which higher-level, complex behaviours are produced from sets of reiterated interactions between more basic elements and their functions (e.g. individuals or organs) [1, 2].

The concept of self-organisation has achieved particular popularity in models for advanced information and communication networks, as in [3, 4], with early references dating back the 1980s, e.g. [5]. Among the plethora of definitions that have been proposed in this field, common conceptual ground is found, firstly, in the mode of adaptation of the systems, which occurs in ad-hoc, situated and dynamic fashion rather than along predetermined routines, and, secondly, in their adaptive qualities, which lie in their distributed and localised structure, from whose operations more complex structures and functions emerge in bottom-up fashion. One may expect that these properties of the model translate to the level of the target system, i.e. that which is to be designed. If the model is successful, these properties of the network will enable real-world applications that are embedded in, and adaptive to, the ever-changing and sometimes hardly predictable environment of human actions and interactions. Or so it seems.

The purpose of this essay, which argues from a philosophy of science perspective, is to raise awareness to some possible implications of the use of the concept of self-organisation in the design of information and communication networks. It will do so by first generally discussing the epistemic role of models in science, in order to apply the outcomes of that discussion to the present case.

2 Models in Science

In the natural sciences, the target system of a model, in most cases, is the explanandum of a theory. The question to be answered by introducing a model normally is: What properties of an entity or what kind of causal interchange with its surroundings that are inaccessible to observation by currently available means make it behave in a certain way? In the absence of direct evidence of the physical and causal structures in question, an answer is sought in the selective ascription to the target system of properties known to pertain to entities from other domains. Thus, a relation of analogy is established.

The establishment of such analogies is an important step in the construction and application of scientific theories. Analogies may be applied in an informal, 'psychological' way, making the domain of the theory intelligible by using the structure and behaviour of some fairly well-explored system to describe the predicted structure and behaviour of the target system. The importance of models even on this informal level can be observed in quantum theory, which arguably is so notoriously hard to comprehend because there is no better-known system available to stand in for that theory's highly abstract notions [6, p. 45 f].

In a more systematic fashion, analogies may also serve to establish correspondence rules between theoretical and empirical concepts, which otherwise would remain detached from each other and empirically unproductive, and they may serve to systematically expand the domain of application of a theory. To do so, clear definitions of the extension of both the target system and the model are required. Only a certain part of the model can be expected to correlate with the target system, and only in certain ways.

On these grounds, several criteria for scientific models are articulated in the philosophical literature:

(I) It should be spelled out precisely which properties are deemed analogous between model and target system [6, 7]. The selection should be such that the roles played by the chosen properties in the different systems should be *isomorphic* to a certain extent [8]. In computer models of the human mind, the functions of mental traits are explained by ascribing certain functional properties of computers to them, but processor architecture or storage methods are not among these properties.

(II) It should be monitored what character the relation of analogy is meant to have when introducing the model, and what character it turns out to have after testing the model. A distinction can be made between *positive*, *negative* and *neutral* analogies [7]: relations between model and target system that are already known to hold, relations that are already known not to hold, and, most interestingly, relations that, at the current stage of inquiry, cannot yet be proven to hold, but will help to evaluate the present theory when it is eventually found to hold or not to hold.

(III) It should be explicated in which way the analogy is meant to hold. Models may represent their target systems in a variety of ways [9]: They may *abstract* from the concrete properties of the target system in focusing on analogies in effects, functions, or behaviours in general (e.g. in being a computer model of a biological system); they may be *idealisations* of the target system, in having certain properties that the target system does not, and probably cannot, have (e.g. noise-less transmission or point masses); and they may be chosen to *approximate* the target system's behaviour (e.g. in assuming a mean value for a variable effect).

(IV) It should be defined what kind of structure the analogy is to have: The most fundamental distinction is to be found between *substantive* or "material" and *formal* analogies [6, 7]. The former may be comprised of physical objects, such as the wire-and-plastic structure of a DNA model, or of descriptions in natural language. Stricter conditions apply to formal analogies, in that they only hold if an identical formal structure can be proven to underlie the behaviour of different systems. If, for example, a behavioural pattern within some population can be represented by a certain algorithm, this pattern may serve as a formal model of the interactions of network nodes only if the same algorithm is to be applied to the latter.

These criteria, in different constellations, cater for all kinds of models in the natural sciences. They serve to define both the extension of the model (what target domain it refers to) and its intension (what it says about that domain). I will now discuss the applicability of these criteria to models in the realm of technology, and then proceed to their possible implications for the present case.

3 Models and Technology

The most obvious distinction between models in science and models in the realm of technology lies in their direction of fit. Models in science are meant to help explaining a given phenomenon, being generally models *of* a certain target system. Any model that is found to misrepresent the properties of its target system, e.g. in mistaking a negative analogy for a positive one (see III above), or in missing out one important property of the target system (see I above), is either falsified or must be restricted in its domain of application. If however the design of artefacts is concerned, and if the model is meant to be a model *for* the target system, i.e. the artefact to be designed, such misrepresentation may also be a case of faulty implementation, and thus of lacking world-on-model fit.

Moreover, what is represented by a technological model is not something that has a history of existing and being observed within the real world in the same way as a natural system. What actually has to be included in the model, and in precisely which way it needs to fit onto the target system, is thus less clear from the outset. In the worst case, it is only found out on the real-world implementation of the model. Most prominently, choosing the wrong properties or choosing the wrong level of abstraction or idealisation may result in the overall failure of the technological system so modelled [10, 11].

On the positive side of the balance, approximations in formal models, unlike in the natural sciences, need not be analytical in order to count as a solution, as their criteria of success are pragmatical: If the model is found to work in engineering practice, it is sufficiently confirmed [11]. In the present case, these observations on the role of technological models are of particular importance to the question of how the environment of the target system is taken into account.

4 Self-Organisation as a Model for Networks

Advanced contemporary networked systems, when modelled as self-organising systems, are related to their environments in two particular ways that distinguish them from other technological systems:

A. The environment is part of the model. If the systems in question are modelled on natural systems and their behaviour in natural environments, abstraction and idealisation will become particularly challenging tasks. First and foremost, self-organisation in natural systems is itself a highly abstract and idealised scientific model of the formal kind, with the purpose of revealing one common trait among a plethora of physical, chemical and biological phenomena. It may be decently articulated mathematically, but in its implications, the concept of self-organisation is not fully explored to date [2]. Consequently, the mode of abstraction and idealisation will be different in each case of application to new domains, requiring attention to a variety of additional factors, since the specific kinds of interaction of the functional elements of each system with and within its respective environment are the *topic* of the model, not something that could be omitted from the picture in any way. Algorithms of ant behaviour will have to take different system-environment relations into account than, e.g., models based on cellular automata, and they will be applicable on different levels of abstraction, idealisation and approximation. The models themselves, as they stand in biology, may be found not to provide sufficient guidance to this task.

Moreover, the more precise a model is to be, and the richer its repertoire of analogies is to be, the more difficult it will be to address the right level of model-building. If the analogy is very informal, there will be few restrictions on its application, and there will be little risk of failure beyond having picked a bad metaphor, but its epistemical value will be limited to phenomenological similarities with inspirational function, as in [3, contribution by Flake et al.]. If the analogy is highly formal, it will be applicable in a straightforward and systematic fashion, but its scope will be limited, too, since it only covers one or a few systems, and since the set of properties it includes will be small, as in [3, contribution by Dousse / Thiran]. Yet, unlike for scientific models, all that precision might ultimately be in vain, as the system so modelled may turn out to be faultily implemented in its environment. If however one chooses the middle ground of a systematic heuristic, as in [4, 5, 12], model-building might prove both a very difficult and very rewarding endeavour. If one uses natural self-organising systems as a (material) analogy that shall be both of comprehensive scope *and* of systematic value – if, for example, it is to provide us with neutral analogies that can be tested for becoming positive ones, so as to advance our inquiry –, the selection of the right set of properties to be modelled and of the correct level of abstraction and idealisation, *with particular respect to the system's environment*, rather than formal precision, assume superior importance.

B. The modelled system is embedded in its environment. The environment of a system, it is argued in some corners of evolutionary biology, does not reduce to the spatio-temporal surroundings of that system; instead, it is coextensive with those conditions in its surroundings that are relevant to its further behaviours – which may vary significantly between different systems even if placed in the same surroundings [13]. The specific organisation of the system and its interactions with and within its surroundings thus define which conditions are the relevant ones. If networked systems are designed as self-organised, they will, at least implicitly, incorporate models of their environment, and, if successful, they will be adaptive to a certain set of conditions and variations therein.

However, although the behaviours of their human counterparts belong to the conditions relevant to the systems, and thus to their environments, it does not follow that these systems are adaptive towards human actions and purposes from the latter's perspective, so as to be perceived by them as embedded in *their* environments. First of all, the property of self-organisation does not necessarily apply to all levels of the system. As the analogy proposed by the model is of partial nature *by definition*, other parts or other levels of the system's organisation may be of a different kind, and they may well be so perceived. There is no usable body of evidence to date that could tell us how self-organising networked systems actually fit into human environments, and how they are actually being perceived, as they have no history of being part of such environments. In order to achieve a systematic match between self-organising properties modelled into the systems and their intended perception, the inclusion of models of human beliefs, desires and actions with regard to these systems seems recommended.

For example, communication networks may be modelled along the principles of self-organisation in fairly detailed and formal fashion on a certain level, as in [5, 12]. The aim is a coherent and stable, yet flexible infrastructure for all varieties of uses under all varieties of circumstances. However, on this first, infrastructural level, the systems' adaptivity to human behaviours is limited to the latter's movements in space-time and to the transition between different usage contexts. No attempt is made to anticipate, and adapt to, the purposes of human beings in terms of what world affairs and accomplishments they are directed at. Yet these purposes define what kinds of services are actually required and used, and what contents are communicated. Addressing these contents may be facilitated by a self-organising systems architecture, but if its model indeed contains a neutral analogy that might capture human purposes proper, this analogy will have to be independently validated – on pragmatical grounds.

5 Conclusion

The concept of self-organisation not only is a difficult concept in itself, for its combination of complexity, abstraction and intended scope. In the analysis and design of advanced information and communication networks, it poses particular challenges, as its function is not to provide explanatory models of the structure and behaviour of natural systems in their specific environments, but to provide design models for the structure and behaviour of technological systems in their environments – whose conditions are difficult to predict. Still, there may be constructive uses for the concept of self-organisation – in spite of the criticism it received even from some of its protagonists [1, 2], and in spite of the inverse correlation between its popularity and the agreement on its definition.

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