

The ontology of Operations Research and Complexity Theory: a critical analysis

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PREAMBLE

Key terms: Operations Research, Complexity Theory, epistemology, Paul Cilliers

Operations Research (OR) refers to analytical and mathematical methods of problem-solving and decision-making. The Institute for Operations Research and the Management Sciences (INFORMS)¹ defines OR simply as “a discipline that deals with the application of advanced analytical methods to help make better decisions”.

Despite a number of recent studies in the area of systems thinking (Mingers and White 2010) and lately in Behavioural OR (Harmalainen et al. 2013) it appears that OR is still mainly inspired by a Newtonian framework that claims that the universe can be understood through a process of reductionism and breaking up of systems into parts in order to understand how the whole works. This viewpoint has been indicated and critiqued as early as 1962 by OR researchers such as R.L. Ackoff, who argues that OR is based on a mechanistic methodology. In fact, Ackoff claimed in 1979 that the “future of OR is past” because of this closed and mechanistic approach of “predict and prepare”. He lists six deficiencies to support his argument and contends that the OR methodology does not take into account the complexity of the large number of role players, their interactions and intricate relationships (Ackoff 1979a). The reductionist approach followed by OR practitioners may have worked in the past but more fitting paradigms for the present should also be considered and where appropriate, should replace the old paradigm of linearity. One such new paradigm may be found in Complexity Theory.

Complexity Theory, although difficult to define, offers a new and different theoretical framework for the way in which certain systems can be understood. The late South African philosopher Paul Cilliers describes a complex system in terms of ten characteristics, such as being an open system consisting of a large number of elements that interact in a dynamic and non-linear way with each other (Cilliers 1998). Complex systems also exhibit other properties, such as emergence, boundaries, lack of complete knowledge and ethical issues. These characteristics and properties clearly indicate that a complex system cannot fully operate in the same paradigm of order in which OR traditionally operates. It can be argued that the majority of typical OR applications function in a complex reality which can be described in terms of the characteristics of a complex system. This study therefore proposes that OR can benefit from employing a complexity theory approach to its field so as to afford new fundamental insights to the methods for engaging with decision-making in the real-life context in which OR is used. This goal may be translated into the following hypothesis: By acknowledging that decision-making happens in a complex reality (with the characteristics as stated by Cilliers) and by

¹ <https://www.informs.org/About-INFORMS/What-is-Operations-Research>

verifying that the structures and environments in which OR approaches are applied are complex, new contributions could be made to the epistemology that fundamentally informs the field of OR.

In order to reach this goal – with the possibility of a fundamental change in how decision-makers view the process of OR based decision making – the study will start with a brief introduction and overview of OR and Complexity Theory. The development of both these fields are discussed and especially Ackoff's critique regarding the short-comings of the traditional OR methods that are based on analytical and mathematical modelling so as to develop better optimisation models. It will then be argued that the traditional models that are used in OR are mainly assuming that the nature of the world is machine-like and that OR models assume that formal mathematical models can explain and predict the reality in which they are employed perfectly (positivism). To criticise and broaden this traditional OR approach (and to explain the shortcomings thereof in light of real life problems) Complexity Theory will be introduced and discussed (through the work of Paul Cilliers) as a way in which the complexity of the world is acknowledge. Based on the understanding that the world is not mechanical but complex in nature (as explained by Cilliers and the characteristics of complex phenomena), one sees that the assumptions on which traditional OR theories based their field of study are in many cases contentious and that the accompanying epistemology and related methods are limited and/or flawed. By aligning OR epistemologies with the acknowledgment of complexity, new methods for modelling decision making could be developed. In light of Complexity Theory, these methods should be cognisant of complexity characteristics such as emergence, boundary setting, provisional knowledge and what (ethical) responsibilities accompany such methods. Some concrete examples will therefore be given as part of this study of how OR could be influenced by applying a complexity lens. The overall focus will thus be, as the title suggests, on the epistemological implications of complexity thinking for OR.

In accordance with rule A.7.2.5 of the "General Academic Rules" of the North-West University, this mini-dissertation is presented in the form of an article. The article will be presented for publication in the *European Journal of Operational Research* at a later stage (the guidelines for publication in this journal are included in the appendix).

The article contains the following sections

1. Introduction
2. Operations Research: Epistemological questions
3. Complexity Theory: An alternative epistemology
4. Operations Research in the context of Complexity
5. The general reductionist epistemology of Operations Research
6. Aligning the epistemology of Operations Research with complexity
7. Conclusion

The next section presents the research article, with a bibliography and a summary in accordance with the prescriptions of the *European Journal of Operational Research*. In the final sections of this mini-dissertation some general conclusions, limitations and recommendations for further research are presented. The appendix contains the prescriptions for research articles submitted to the *European Journal of Operational Research*.

RESEARCH ARTICLE

The Ontology of Operations Research and Complexity Theory: a critical analysis²

Abstract

Operations Research (OR) is a discipline that is mainly concerned with the use of analytical and mathematical techniques and models that are used in problem-solving and decision-making situations. The discipline appears to operate largely in a paradigm of order and has been called mechanistic, with a methodology that is based on the principle of “predict and prepare”. Although this positivistic approach may have worked well in the past, the acknowledgement of the complexity of the real world calls for broadening this approach or epistemology. Complexity Theory is considered here as an approach that can broaden and enrich the epistemology of traditional OR applications. Following a brief introduction to OR and Complexity Theory, an argument is developed that the traditional OR approach is based on the assumption of the world being machine like, and that it leads to an epistemology and related methodologies that are limited and/or flawed. It is then argued that Complexity Theory (through the work of the philosopher Paul Cilliers) acknowledges the complex nature of the real world and helps one to identify the characteristics of complex phenomena. By aligning OR epistemologies with the acknowledgment of complexity, new methods for modelling decision making could be developed. In light of Complexity Theory, these methods should be cognisant of characteristics such as emergence, boundary setting, provisional knowledge and what (ethical) responsibilities accompany such methods. Some concrete examples is given of how OR could be influenced by applying a complexity lens in order to highlight the epistemological implications of complexity thinking for OR.

1. Introduction

Operations Research (OR) is mainly concerned with the use of mathematical techniques to formulate models that can be used to assist decision makers in specific decision-making situations. In 1979 Russel Ackoff, the OR specialist who also taught philosophy, published his well-known paper “*The future of Operational Research is past*” (Ackoff 1979a). In this paper he argues that the OR methodology is in general inappropriate and that deficiencies exist in the concept and practice of optimisation (the basis of OR). Ackoff also suggests that there are problems in the way which operations researchers pursue objectivity in their work. He proposes that systems thinking, with the associated concept of expansionism (as opposed to reductionism), be applied to OR. The importance

² The term ontology is used in the title in a very broad sense and a more appropriate term (as one of the external examiners suggested) could be epistemology

of systems thinking has already been pointed out in earlier work by Ackoff (1962) and others. A large number of studies in different application areas have been performed in the area of systems thinking, among others theories such as a general systems approach, cybernetics, system dynamics, problem structuring methods, critical systems and multi-methodologies. Mingers and White (2010) provide a review of the contribution of these theories and methodologies to OR. A more recent development in OR that also attempts to address some of the reductionist deficiencies is Behavioural OR, which studies the behavioural aspects of the use of OR in problem solving and decision support (Hamalainen et al. 2013).

Despite a number of recent studies to address the reductionist deficiencies it appears that OR is still mainly inspired by a Newtonian framework that claims that the universe can be understood through a process of reductionism and breaking up of systems into parts in order to understand how the whole works. As mentioned above, this viewpoint has been indicated and critiqued as early as 1962 by OR researchers who argued that OR is based on a mechanistic methodology. Ackoff lists six deficiencies to support these arguments and contends that the OR methodology does not take into account the complexity of the large number of role players and their interactions and intricate relationships (Ackoff 1979a). The reductionist approach followed by OR practitioners may have worked in the past but more fitting paradigms for the present should also be considered and where appropriate, should replace the old paradigm of linearity. One such new paradigm may be found in Complexity Theory.

Complexity Theory, although difficult to define, offers a new and different theoretical framework for the way in which certain systems can be understood. The late South African philosopher Paul Cilliers describes a complex system in terms of ten characteristics, such as being an open system consisting of a large number of elements that interact in a dynamic and non-linear way with each other (Cilliers 1998). Complex systems also exhibit other properties, such as emergence, boundaries, lack of complete knowledge and ethical issues. These characteristics and properties clearly indicate that a complex system cannot fully operate in the same paradigm of order in which OR traditionally operates. It can be argued that the majority of typical OR applications function in a complex reality which can be described in terms of the characteristics of a complex system. This study therefore proposes that OR can benefit from employing a complexity theory approach to its field so as to afford new fundamental insights to the methods for engaging with decision-making in the real-life context in which OR is used. This goal may be translated into the following hypothesis: By acknowledging that OR related decision-making happens in a complex reality (with the characteristics as stated by Cilliers) and by verifying that the structures and environments in which OR approaches are applied are complex, new contributions could be made to the epistemology that fundamentally informs the field of OR.

It is important to note that Complexity Theory is listed as one of the recently developed theories in systems thinking (Mingers and White 2010: p. 1148). However, Complexity Theory is usually linked to Chaos Theory and the two terms are ostensibly used as synonyms for the same theory (Merali 2006: p. 219). In this study the discussion of Complexity Theory will be based on the philosophical work and contributions of the late South African philosopher Paul Cilliers (1998) and will not include the mathematical and computational views that are often derived from Chaos Theory. The reason for this exclusion is that Complexity Theory as described by Cilliers does not value sensitivity to initial conditions – the underlying concept of Chaos Theory is the notion of small occurrences or changes that significantly affect the outcome of seemingly unrelated events. Furthermore, while chaotic behaviour in a technical sense results from the non-linear interaction of a relatively small number of equations, complex systems imply an interaction of a large number of components (Cilliers 1998: p. ix). Merali (2006) supports the idea of a wider class of complexity systems, because a chaotic system is technically a deterministic system that is just difficult to predict. Merali argues that it is more realistic to see complexity science as an emergent paradigm shift in the Kuhnian sense (Merali 2006: p. 219), a view shared by some operational researchers (Mingers and White 2010: p. 1148). The exclusion does not imply that Chaos Theory may not contribute to further insights into Complexity Theory. This study will therefore exclude systems thinking and its associated theories and methodologies and will only concentrate on Complexity Theory as presented by Cilliers (1998). No claim is made that the computational and mathematical models in OR are wrong or of little use. These models are necessary for the development and progress of OR and fulfil an important role in many circumstances. They have produced wonderful results in the past and will continue to do so in a great variety of application areas. The argument is rather that these models can be enriched and further developed by aligning OR epistemologies with the acknowledgement of complexity.

In order to reach the stated goal of the study – with the possibility of a fundamental change in how decision-makers view the process of decision making – the article will start with a brief introduction and overview of OR and Complexity Theory. The development of both these fields are discussed and especially Ackoff's critique regarding the short-comings of the traditional OR methods that are based on analytical and mathematical modelling so as to develop better optimisation models. It will then be argued that the traditional models that are used in OR are mainly assuming that the nature of the world is machine-like and that the OR models assume that formal mathematical models can explain and predict the reality in which they are employed adequately (positivism). To criticise and broaden this traditional OR approach (and to explain the shortcomings thereof in light of real life problems) Complexity Theory will be introduced and discussed (through the work of the philosopher Paul Cilliers) as a way in which the complexity of the world is acknowledged. Based on the understanding that the world is not mechanical but complex in nature (as explained by Cilliers and the characteristics of complex phenomena), one sees that the assumptions on which traditional OR theories based their

field of study may be wrong and that the accompanying epistemology and related methods may be seen as limited and/or flawed. By aligning OR epistemologies with the acknowledgment of complexity, new methods for modelling decision making could be developed. In light of Complexity Theory, these methods should be cognisant of emergence, boundary setting, provisional knowledge and what (ethical) responsibilities accompany such methods. Some concrete examples will be presented as part of the study on how OR could be influenced when applying a complexity lens. The overall focus will thus be, as the title suggests, on the epistemological implications of complexity thinking for OR.

Complexity Theory is chosen as the comparative paradigm and epistemology to OR, because Complexity Theory advocates and offers explanations for concepts such as non-linear environments and non-hierarchical structures which are regularly experienced in OR applications. Investigating and relating a specific area of interest to Complexity Theory is a known and acceptable method to attempt to gain a deeper understanding of a subject. Examples of studies where this has been done include disciplines such as music (Crowe 2004), mathematics (Mowat and Davis 2010), education (Morrison 2006), staff development (Fong 2006) and information systems (Merali 2006). The principles of Complexity Theory have also been applied to decision-making and OR-related problems, for example by Paul et al. (2014), who developed a management decision-making model based upon a complexity perspective and with reference to a bee optimisation algorithm. Nature-inspired algorithms based on the behaviour of, for example, bees, birds and fish (particle-swarm optimisation) are well-known OR techniques and are regularly employed by operations researchers in a variety of management science problems.

2. Operations Research: Epistemological questions

Operations Research as a discipline has been defined by many researchers, but a common element found in all these definitions is that OR is concerned with computational and mathematical techniques for *decision making*. Even more interesting is the explanation by Gass and Assad (2005: p. i), who emphasise that the human element is an active participant in OR, which they define as the science of decision making. There is general consensus that the birth of OR was during the years of World War II, when mathematical techniques were employed in warfare. There were, and still are, many developments in OR and in the different techniques used. However, the main development took place during the 1940s, when George Dantzig developed the simplex method for solving linear programming (LP) models (Eiselt and Sandblom 2010: p. 3). These types of optimisation models play a significant role in OR and are among the most powerful tools in OR. A typical LP model is formulated as some objective function (e.g. a profit or cost function), which is to be maximised or minimised subject to certain constraints (e.g. resource limitations), which are also expressed as linear

functions. Optimisation then refers to the process of finding the best values for variables, or in the context of decision making, finding the best values for a particular measure of performance (Baker 2011: p. 1). The basic formulation (for a single objective problem) is as follows:

Maximise/Minimise $f(\mathbf{X}) = \mathbf{c}\mathbf{X}$ subject to $\mathbf{A}\mathbf{X} = \mathbf{b}$ and $\mathbf{X} \geq \mathbf{0}$ where $\mathbf{c} = (c_1, c_2, \dots, c_n)$ is a row vector of coefficients, $\mathbf{X} = (x_1, x_2, \dots, x_n)$ and $\mathbf{b} = (b_1, b_2, \dots, b_m)$ are column vectors. $\mathbf{A} = (a_{ij})$ and $\mathbf{0}$ is an n -dimensional null column vector.

Ackoff noted six deficiencies with regard to the optimisation concept used in OR. According to Ackoff the methods used in OR are purely analytic, while the models are predominantly closed and mechanistic in nature – it relies on one elementary relationship, namely cause and effect, which results in a deterministic concept of reality (Ackoff 1979a: pp. 95,97). He proposes a systems thinking approach in which “*purposeful systems that contain purposeful parts with different roles or functions and that are themselves parts of larger purposeful systems*” can be designed (Ackoff 1979a: p. 96). This approach will then facilitate a process whereby systems can effectively serve their own purposes (self-control), the purposes of their parts (humanisation) and the purposes of larger systems of which they are part (environmentalisation).

In the context of an OR problem, these concepts may be explained in terms of the well-known facility location problem, which can be solved by means of a linear programming model. Suppose that a number of warehouses have to be built on predetermined potential sites. The objective is to determine the appropriate number of warehouses and the sites where they should be built in such a way that the demands of all customers are met at a minimum cost. If the only ultimate goal is to build the warehouses to serve all the customers at an absolute minimum cost, without taking any other factors into account, then the problem and solution is focused on its own purposes (self-control). If other factors are taken into consideration, such as the impact on people and communities living in the area where the warehouse will be erected, then the solution will also serve the purposes of their parts (humanisation). For example, a warehouse may cause unemployment in a community where people (small businesses) were employed to store and transport products which may now be available from a nearby warehouse. If the influence on the larger region and environment is also taken into account, then the purposes of larger systems (environmentalisation) are considered. Quality of life may be reduced due to pollution, noise and destruction of eco-systems caused by building activities, etc.

For Ackoff, OR is almost exclusively concerned with self-control, thus with serving its own purpose (Ackoff 1979a: p. 96). Based on this motivation, Ackoff (1979a: p. 103) identifies the following deficiencies of OR:

- 1) A need for decision-making systems that can learn and adapt – something that an optimising system cannot do.

- 2) Taking into account values that are relevant to quality of life – (called *aesthetic values* by Ackoff).
- 3) Model abstraction of systems of problems (called *messes* by Ackoff). According to Ackoff, problems cannot be treated effectively by decomposing them analytically into separate problems.
- 4) A synthesising planning paradigm should be adopted, as opposed to the problem-solving paradigm of “predict and prepare” that is employed by OR.
- 5) Interdisciplinary nature and interaction are requirements to deal with messes (complex systems).
- 6) In addition to these aspects related to optimisation, Ackoff also noted a sixth deficiency pertaining to the concept of objectivity in OR. This issue relates to all those who can be affected by the outcome of a decision-making process.

The concerns of the deficiencies of OR raised by Ackoff have a common denominator in the sense that they are focused on typical human characteristics and they require a more holistic, integrated approach to address. Keywords indicating this include “learn and adapt”, “quality of life”, “messes”, “synthesised planning” and “interdisciplinary and interaction”. Furthermore, it also seems that Ackoff believes that a too mechanistic approach is followed in solving problems – this approach does not take into account the complexity of the large number of role players, their interactions and intricate relationships.

It may be said that all six issues raised by Ackoff are fundamental issues in OR. They indicate that OR as a discipline has built its conceptual foundations on the assumption that reality works like a clock or a machine that adheres to principles such as order, controllability, interactions that are linear e.g. a certain amount of input guarantees an equal or proportional amount or effect in output and initial conditions that lead to predictable outcomes (deterministic). These conceptual foundations (and six issues raised by Ackoff) are still applicable today, in spite of certain developments (e.g. the systems thinking approach) that may address some of them. Some of the solutions offered by Ackoff himself (in a follow-up paper, Ackoff 1979b) are cosmetic changes that deal with how professional OR societies should function and what should be taught in educational OR programmes. He also suggested that OR should be “undefined”, to get rid of the constraints of the profession. A suggestion that touches on more fundamental issues is the argument that OR should replace its problem-solving paradigm with one that focuses on planning and design of systems. Such a paradigm should, according to Ackoff, be based on a participative principle, a principle of continuity and a holistic principle. These three principles are concerned with planning and Ackoff offered some practical guidelines for how to adhere to them. Although these practical suggestions are necessary to address the deficiencies of OR identified by Ackoff, more fundamental questions may be asked about the nature of OR’s epistemology. It is at this point where Complexity Theory may play an important role.

3. Complexity Theory: An alternative epistemology

Cilliers argues that complexity cannot be given a simple definition – an analysis of the characteristics of a complex system should rather be attempted to arrive at a suitable and general description (Cilliers 1998: p. 2). He distinguishes between complicated and complex systems: Systems that can be analysed accurately, such as a Jumbo jet, are *complicated* while systems that are constituted by intricate sets of non-linear relationships and of which only certain aspects can be analysed at a time, are called *complex* (Cilliers 1998: p. 3). Cilliers view fractals (which form an important part of Chaos Theory) as being complicated and not complex, as claimed by many researchers. He emphasises this distinction as follows:

A complex system is not constituted merely by the sum of its components, but also by the intricate relationships between these components. In ‘cutting up’ a system, the analytical method destroys what it seeks to understand (Cilliers 1998: p. 2).

It is apparent from this description that there are definite links between complex systems and Ackoff’s OR concerns. Ackoff agrees that systems cannot be analysed by looking only at their components but that there are an interdisciplinary relationship and interaction (intricate relationships) among components. For Cilliers the characteristics of a complex system (that will provide the necessary definition or description of a complex system) can be summarised as follows (Cilliers 1998: pp. 3-5).

Complex systems consist of a *large number* of elements that *interact* in a dynamic way. These interactions are *non-linear* and fairly *rich* in the sense that any one element influences, and is influenced by, a large number of other elements. The nature of the interactions are of a *short range* (elements receive information primarily from immediate neighbours) and *loops* occur in the interactions (the effect of an activity can feed back onto the element itself). Complex systems do not operate under *equilibrium* and are usually *open systems* as it is difficult to define borders for the system. Complex systems also have a *history*, which means that the past is co-responsible for present behaviour. Finally, each element in a complex system is *ignorant* of the behaviour of the system as a whole.

It is also important to note that complexity is often viewed from two different perspectives. Morin (2007) distinguishes between restricted complexity and general complexity. The former refers to cases where the goal of scientific practices is to uncover the rules and laws of complexity (Woermann nd: p. 1). This refers to the mathematical and computational approaches which may include the concepts of chaos, fractals, disorder etc. Restricted complexity therefore tries to describe and explain chaotic phenomena mathematically and in ways that reintroduce positivism and reductionism (Cilliers 2010:

p. 41). As explained in the introduction, this paper is not concerned with the principles of restricted complexity. General complexity, on the other hand, assumes that it is impossible to uncover the rules and laws that govern all phenomena (Woermann nd: p. 2). A more comprehensive description of these concepts as well as the features of complex systems can be found in Woermann (nd).

In addition to the characteristics of a complex system as described above, Cilliers also pointed out that complex systems need two capabilities to deal with changing environments (Cilliers 1998: p. 10): *representation*, which involves storing information concerning the environment for future use; and *self-organisation*, which involves adapting the system's structure when necessary.

In order to understand complex systems it is necessary to model them. Cilliers (1998: p. 13) identifies two approaches for this. Cilliers describes the first approach – the *rule-based* system – as inappropriate for understanding complex systems. The second approach is termed *connectionist* models and is based on the well-known neural networks that are widely used in computer science. Cilliers argues that these connectionist models share the characteristics of a complex system and should be more useful for understanding complex systems than rule-based models (Cilliers 1998: p. 21). Follow-up work on Complexity Theory by Cilliers indicated that there are a number of aspects of complex systems that may be applicable to this study and to OR. Some of the more important issues include the concept of knowledge and what constitutes knowledge in a complex system (Cilliers 2002, 2000a); the role played by limits and boundaries in a system and how it may possibly lead to reductive descriptions of a complex system (Cilliers 2002); the status of rules when dealing with complex systems (Cilliers 2000b); and ethical decision making (Woermann & Cilliers 2012).

4. Operations Research in the context of complexity

In this section the complexity in the context of reality in which the majority of typical OR applications functions is described. This will be done in terms of the characteristics of a complex system as presented by Cilliers (1998: pp. 3-5). Applications where the objective is simply to seek an optimal answer to an obvious mechanistic problem (e.g. the optimal loading sequence of different items onto a truck) are not considered in the discussion. The facility location problem where a number of warehouses have to be built on pre-determined possible sites will be used as a representative example of a typical OR application in a complex real world context. This example was introduced earlier in the paper when reference was made to the work of Ackoff.

4.1 OR applications consist of a large number of elements

The OR discipline is grounded in mathematics and mathematical statistics and is therefore made up of a large number of concepts, ideas and techniques that are used and applied in an even larger number

of combinations. If these elements only are taken into consideration, it implies a finite number of elements which imposes some sort of a boundary on an OR system. However, according to Mowat and Davis (2010: p. 4) and Cilliers (2008: p. 47) it is unavoidable (and in fact required) that a study of a complex system will have some sort of an artificial boundary from the observer's viewpoint.

In her study on complexity and information systems, Merali (2006) pointed out that a network economy and network society has emerged and that the world currently should be seen as a "networked world". This view strongly supports the idea that an OR application does not exist in isolation, nor does the set of techniques and concepts on their own constitute an OR system. Other interacting elements are always present, such as individuals, societies, the environment etc. The OR application described earlier is also strongly related to an economic application which interacts with a large number of economic elements such as people, the economy itself (price, supply, demand, labour interest rates etc.) and the environment. All these external interactions do not contribute to the OR application in a deterministic way but rather interact and merge with the application. It is difficult to identify all components of all elements and to fit them into a coherent whole to provide an exact description of the OR application and all its elements.

4.2 The elements in an OR application interact dynamically

An OR model can only be meaningful in the real life context in which it is applied. In other words, if the model does not interact with the environment in which it operates, it becomes meaningless. The variables in an OR model do not only interact mathematically with each other but they also represent a certain relationship with reality, economic variables, resource variables and a host of others, all present in the warehouse example, and they imply an interaction with the environment and individuals which may be continually shifting and changing. The OR application, and also specifically the warehouse location problem, are therefore used in the combined efforts and relationships caused by the dynamic interactions of a large number of elements. This interaction between the OR application and reality is not necessarily always of a physical nature but may also occur as the "transfer of information" (Cilliers 1998: p. 3).

4.3 The level of interaction among elements in an OR application is fairly rich

Advances in the field of OR is the result of relationships among different elements which include mathematical concepts as well as application concepts. New developments are therefore formed from interactions among existing concepts and elements. The implementation of an OR model, as described in the example, will result in a rich interaction with, for example, the environment. An economic activity, as a result of the OR model implementation will cause a large number of interactions with economic and other agents.

4.4 The interactions in an OR application are non-linear

Non-linearity guarantees that small causes can have large results and vice versa (Cilliers 1998: p. 4). This is exactly what happens in the type of OR application used here as an example. The implementation of a relatively small and simple OR model may produce large economic and/or social returns. Conversely, a comprehensive and significantly large model associated with costly development (in terms of time and money) may have no or very little impact if the model proves to be trivial, incorrect or inadequate. Furthermore, Cilliers (1998: p. 120) states that the principle of asymmetry is closely related to the principle of non-linearity. The OR application described here contains strong elements of a competitive nature; i.e. the best location at the lowest cost. This competitive nature causes an asymmetrical system of relationships. If there were a symmetrical relationship amongst the variables (e.g. no difference in the cost to deliver goods at different locations), there would have been no need for an OR, or any other model. Non-linearity, asymmetry and competition (which are all present in OR applications) are inevitable components of complex systems (Cilliers 1998: p. 120).

Considering the OR discipline itself, a single (small) idea may also cause large-scale changes and may even lead to new knowledge, schools of thought and applications. One example of this is the application of activity analysis by Farrell (1957) to the measurement of productive efficiency, which was generalised by Charnes et al. (1978) as a new OR approach, known as Data Envelopment Analysis (DEA). DEA today is a new subfield within the OR discipline which produced literally thousands of research papers and which has led to specialist international conferences and journals.

4.5 Interactions in an OR application have a fairly short range

The formulation and implementation of an OR model may have a profound impact on elements locally or close to the application area. The aim of an OR model is to bring about change which will hopefully result in improvement. This change occurs mainly at a local level and close to the application. For example, building a warehouse (by using an OR model) will have an impact first and foremost on elements close to the building activity, for instance economic activity, social activity (employment, communities etc.), pollution, eco-system and so forth.

Although spatial and temporal location plays the most significant role, the interactions do not necessarily have to be of a short range only – interactions may also be wide-ranging (Cilliers 1998: p. 4). The success or failure of an OR model can also have a wider effect than just on the immediate environment. Economic activity at a regional level that also has an impact at national level is an example of such wide-ranging interaction. The ideas, concepts and techniques used in an initial model may permeate other problem areas, which may result in new OR model formulations – this may provide another dimension of the interactions in OR models and OR applications.

4.6 There are loops in the interactions among the elements in an OR application

In OR as a discipline there exist continuous feedback and interconnected loops. For example, the result of a basic linear programming model has led to extensions and new developments such as fractional and goal programming. The development and application of an OR model have also clear and definite loops and interactions that feed back onto itself. A successful OR model will deliver good results while the opposite is true for an unsuccessful model. If there were no feedback on the model, the model would not be necessary and the formulation of the model would have been a useless exercise – OR models would not have been formulated if there were no feedback or results. Feedback may in certain cases not be immediate but may occur only after some time has expired. The building of a new warehouse, for example, may influence the economy in a positive or negative way after some time – this is unpredictable in the context of the real world. Further examples of this are the complexities of job creation and social communities.

4.7 An OR application functions in an open system

An OR model formulation on its own should be regarded as a closed system that is described or defined within a formal description. An OR model can therefore not be called a complex system without qualification. However, to formulate an OR model in a proper way the modeller or decision-maker is confronted with an open system in real life where there are a large number of elements that may have an influence on the formulation. The model may be bombarded with input from the physical, cultural and intellectual application environment. Once the model has been implemented and applied to a specific problem area, the application becomes a truly open system as it becomes impossible to identify a precise boundary of where the impact of the model stops. To confine the results of an OR model to a set of variables, which take on certain values, would therefore be a gross oversimplification.

4.8 OR applications operate under conditions far from equilibrium

De Villiers-Botha and Cilliers (2010: p. 34) explain that our interaction with the world is dynamic and as the environment changes, adaptations are made. The majority of OR applications are aimed at dealing with the improvement and/or adaptation of how we interact with the world. The warehouse model may be a result of the dynamics of supply and demand; a recession; a political system; technology etc. In a symmetric or equilibrium state there would be no need for change, adaptations or management science models. Cilliers rightly pointed out that *equilibrium* is another word for *death* (Cilliers 1998: p. 4).

4.9 OR applications have a history

OR applications are greatly influenced by its history. Successful models may be re-used or improved while unsuccessful models are changed or discarded. The history of an OR application as well as the context in which it was applied, determine the future, the nature and, in a sense, the identity of similar models and applications. The result of an OR model, as in the warehouse example, can no longer be seen as a once-off objectively given result by merely looking at the optimal answer that was generated by the model. Traces of the application of the OR model persist long after the actual implementation – the meaning of the OR model is therefore dependent on past interactions of similar models with other elements. This is consistent with Cilliers's view that the history of a complex system is a collection of traces distributed over the system and is always open to multiple interpretations (Cilliers 1998: p. 122).

Associated with history is the concept of memory. It is doubted whether mathematics have a memory (Cilliers 2010: p. 40), and by implication this would mean that OR does not have a memory either. Although this may be true for an OR model in isolation, such a model does show signs of memory once it has been implemented, as was indicated earlier in the discussion of the influence of successful models and failures. This memory also appears to be contingent and dynamic (a characteristic of a complex system (Cilliers 2010: p. 40)) as the memory will vary from application to application – even when the same type of model is applied in more than one case.

4.10 Each element in an OR application is ignorant to the behaviour of the system as a whole

Although a mathematical relationship exists among the variables in an OR model, the elements in the model are ignorant of the behaviour of the system as a whole. An element reacts only to information available to itself and remains unaware of what happens to other elements or their behaviour. The building of a warehouse at location x is based on information close to the activity, such as the building cost locally at location x ; the number of clients at or in close proximity to location x ; storing costs at location x , etc. Other elements or their behaviour are unknown, for example the impact on the economy (interest rates, confidence etc.).

Cilliers (1998: p. 122) warns that this characteristic should be carefully considered. Other characteristics have already indicated that elements respond only to local information (short range); that this information is rich; and that single elements are not significant in themselves. The point being made with the *ignorant* characteristic is that single elements cannot contain the complexity of the whole system – if that were true, all the complexity would have to be present in *that element* (Cilliers 1998: p. 5). It goes without saying that no single element in a mathematical OR model can contain the complexity of the whole system.

In a complex real world it is rarely possible to simplify things according to a list of characteristics or properties. Although, based on the ten characteristics above one can indicate the complexity in the context of reality in which OR is applied. In addition to this, Cilliers (2010: p. 40) also emphasised that the ten characteristics identified by him constitute only part of the process that is necessary to claim complexity. For example, an important element in complexity is the notion of emergence. Complex systems have emergent properties, which are not something that can simply be reduced to another point on a list of characteristics (Cilliers 2010: p. 40). The acknowledgment of complexity of the real world context in which OR is applied (based on the ten characteristics), however, is important, because it challenges the field of OR to develop a new epistemology and related methods to capture and engage with the complex nature of these systems and processes that it aims to understand and influence.

5. The general reductionist epistemology of Operations Research

In section 4 it was indicated that a typical OR application functions in the real complex world, in terms of the characteristics of a complex system. This is apparently consistent with Ackoff's claim that OR should move away from its existing mechanistic methodology. Ackoff claims that OR is almost exclusively concerned with what he terms a *machine-age approach* to problems (Ackoff 1979a: pp. 96-97). It is based on a three-step approach (called *analysis*) where things that need to be understood are taken apart; followed by trying to understand how these parts work – and finally, by assembling the understanding of the parts, the whole is believed to be understood. Something of this apparent positivistic view was already clear in the section on Operations Research where mention was made of Ackoff's concerns, among others that "OR is purely analytic", "models are predominantly closed and mechanistic" and "OR is almost exclusively concerned with self-control". In this section the epistemology of OR will be briefly reviewed. The aim is to indicate that the epistemology of OR is based on the assumption that the world is mechanical and that it disregards the complexity of the nature of the world in which it functions. This will highlight the need for new approaches within OR and therefore, in the next section, OR epistemologies will be align with the acknowledgement of complexity.

Despite the fact that an OR application functions in a real life context (with complexity characteristics), as shown in the previous section, OR is still practiced in a paradigm of order, where the general known assumptions of scientific method and epistemology are followed. These assumptions (also called *positivistic ideas*) have enjoyed widespread acceptance in the Western world since the beginning of the modern period (Delanty and Strydom 2003: p. 13). Geyer (2003: pp. 2-3) points out that the paradigm of order is founded on four basic rules: *order* (everything that occurs is taken to be the effect of a preceding cause); *reductionism* (a system can be understood by observing

the behaviour of its parts and the whole is the sum of its parts); *predictability* (future events can be predicted by using appropriate inputs to a model); and *determinism* (the universe is causally ordered and everything flows along orderly and predictable paths with a clear beginning and a rational end).

It is of course possible to break down the principles of scientific method into a number of finer categories. Crowe (2004: p. 3), for example, mentions *objectivism*, which looks at phenomena from a distance and excludes human contaminants such as bias and emotion. Delanty and Strydom (2003) quote other important tenets of scientific method, such as *empiricism* (which they describe as the experimental basis of all knowledge); *value freedom* (where the demand is made that science should proceed in a neutral manner that is free from personal, ethical, moral, social or cultural values); *instrumentalism* (which refers to the manipulation of the world rather than understanding it, i.e. a tool of prediction); and *technicism* (where techniques and methods are valued higher than results) (Delanty and Strydom 2003: pp. 13-14).

All the scientific assumptions and rules of order are closely related to OR's epistemology and the traditional OR methodologies. They are virtually openly practised in OR, and the OR methodologies described in text books confirm this – descriptions of the mathematical modelling process consistently refer to “selective representation of the situation”, “acquiring data”, “analyse the quantitative model” etc. (Moore and Weatherford 2001; Render et al. 2015; Eiselt and Sandblom 2010). In terms of technicism it is common knowledge how high the majority of OR specialists (or mathematicians) value the techniques and methods used, and it hardly requires any further motivation. Reductionism plays a particularly important role in OR, as decision-makers constantly has to construct abstracts of reality (real problems) in order to formulate a mathematical model. There are however different kinds of reductionism and Preiser (2012: pp. 87-91) refers to three general kinds of reductionism. The first kind is called *ontological reductionism* and refers to the claim that one physical object can be explained in terms of other physical objects. This leads to a linear development view which assumes that complicated processes are made up of identifiable parts and progress from simple to complex and from inferior to superior (Crowe 2004: p. 4). The next kind of reductionism, *epistemological reductionism*, occurs when a scientific discipline is reduced to the principles of another scientific discipline, for instance the idea to explain biology in terms of physics and chemistry. Preiser explains that “[t]he whole analogy of a clockwork universe or that society's behaviour can be explained in universal algorithms rests on reducing non-mechanical objects to an epistemology that favours mechanism and mathematics” (Preiser 2012: p. 89). *Methodological reductionism* is the third kind of reductionism. It refers to the idea that a system is best investigated at the lowest level and that experiments should therefore be defined in such a way that causal effects can be studied.

From these brief definitions it may be concluded that scientific reductionism favours a paradigm of order. The reductionist method has seemingly proven to be successful in the study of OR problems

and its applications. However, Ackoff's concern is that OR is dealing with complex phenomena and human complexities and that a reductionist approach is too mechanistic and deterministic to address all OR problems satisfactorily. This orderly, reductionist and positivistic epistemology with which OR seems to operate is excellently summarised by Geyer (2003) in terms of epistemological expectations and the methodological implications thereof. The epistemological position emphasises that human knowledge will increase over time. Knowledge will bring about order and the increased knowledge will therefore result in greater order. The increased knowledge will then also enable humans to predict and control more and more phenomena. All phenomena have an endpoint, and so does knowledge. The orderly natural sciences (of which OR is part) form the basis in a hierarchy of scientific knowledge; and duplicating this knowledge and methods serves as a justification for orderly science. The methodological implications of this epistemology are that rational foundations are sought, no inherent limits to human knowledge exist and predictable and repeatable experimental results can be obtained. In addition, the primary methodological strategy is the duplication of orderly natural science methods with an ultimate goal of creating universal and parsimonious laws (Geyer, 2003:7). One can thus argue that although OR functions within complex systems in real life (as indicated in the previous section), OR generally operates with a mechanistic, controlled and reductionist epistemology. This epistemology needs to be enriched and broadened to deal with real world complexities so that new methods for modelling decision making could be developed. This will be investigated in the next section.

6. Aligning the epistemology of Operations Research with complexity

The preceding analysis strongly suggests that most of the typical OR applications functions within complexity. Despite this, it appears if OR may still be inspired by a Newtonian framework that claims that the universe can be understood through a process of reductionism and breaking up of systems into parts in order to understand how the whole works. Mortenson et al. (2015: p. 586), for example, argue that OR fits into a dianoetic (conclusions reached by reason or argument) management paradigm. These reductionist approaches may have worked well in the past – it may still even be applicable today under certain circumstances, but more fitting epistemologies for the present – such as Complexity Theory – should also be considered and where appropriate replace the old clockwork perspective that originated from Newton. This view is in line with Ackoff's concern, as pointed out in section 2.

Drawing from the concerns and epistemological deficiencies raised by Ackoff and the brief description of OR and Complexity Theory, it can be deduced that OR – which functions in complexity– uses an epistemology of order (positivistic) while Complexity Theory with its complexity properties – uses a much more “disorderly” and open epistemology. This introduces the question if OR epistemologies (in a paradigm of order) can be aligned to the complex (disorderly)

epistemology of Complexity Theory. Because OR functions in complexity, the link with complexity theory is not only on a practical level, but also epistemological. In analysing this link, it should firstly be acknowledged that OR functions in a system which has a significant number of complex (disorderly) properties and that all OR applications cannot simply rely on a linear sequential approach that assumes that all phenomena are context-free. Such an acknowledgement will open up new avenues not just for the development of OR epistemologies, but also for the acceptance and accommodation of criticism such as those raised by Ackoff. Previous studies in other disciplines, where the existence and value of Complexity Theory were acknowledged, have greatly benefitted from such an acknowledgement. Examples of such studies in music, mathematics, education, staff development and information systems were mentioned in section 1 and are briefly revisited here in order to indicate how a deeper understanding of the subject was gained by linking the various epistemologies to Complexity Theory.

The study by Crowe (2004) on complexity science and *music therapy* emphasises that complexity science “offers music therapy a scientific model that brings greater understanding to the immensely intricate process that occurs in (the) therapeutic discipline” (Crowe 2004: p. 18). Crowe states that it has changed music therapy to be *less concerned with predicting results and more concerned with the process*. It also now seeks to understand, rather than to look for causes.

Mowat and Davis (2010: p. 27) concluded that it is appropriate to consider a system of *mathematical ideas* as a network structure that exhibits the properties of a complex system. Based on this, they claim that insights from network theory (and the associated complexity principles) will assist in the understanding of teaching mathematics and also *lead to more effective teaching of mathematics*.

In the paper on Complexity Theory and *staff development* it is argued that Complexity Theory has provided insight on how to facilitate and plan complexity-based staff development. It is also particularly useful to *understand change* and to prepare for change – in some instances complexity-driven staff development may even initiate a change process (Fong 2006: p. 12).

In order to understand and accept that the dynamics of *Information Systems (IS)* in a networked world can no longer be treated with traditional scientific methods, Merali posits that a paradigm shift in the IS discipline is necessary. Through an exploration of the concepts of Complexity Theory, and its usefulness for developing IS theory and practice, it is then claimed that “complexity science furnishes us with the concepts and tools for *building multi-level representations of the world and for making sense of the dynamics of emergence*” (Merali 2006: p. 226).

Finally, in the study regarding *decision-making* with specific reference to the bee algorithm (an OR technique), Paul et al. (2014) concluded that a complexity perspective is highly appropriate and

assists with the explanation of different properties of decision-making in a particle-swarm optimisation context.

In section 5 it was argued that OR's epistemological nature is closely related to the positivistic paradigm, or rather the reductionistic natural science paradigm. Certain significant characteristics of complexity in OR applications should, however, be acknowledged – as indicated in section 4. The acknowledgment of the existence of complexity properties (identified in a list of 10 characteristics) in the context in which OR is applied links OR to Complexity Theory. To enrich and broaden OR's epistemologies through Complexity Theory may also open up new perspectives in OR – as the case is for the other disciplines listed above – and it may provide for a more non-mechanistic approach and understanding of OR than its epistemological nature in general allows for. Some new perspectives in OR might be gained for example in term of 1) emergence, 2) the setting of boundaries, 3) lack of complete knowledge and 4) responsibility (ethics) for choices and consequences regarding definitions of boundaries.

6.1 Emergence

Cilliers claims that one of the defining characteristics of a complex system is that it will have emergent properties which cannot simply be reduced to properties of components in the system (Cilliers 2010: p. 40). This characteristic of emergence is defined by Checkland (1993: p. 314) as “the principle that whole entities exhibit properties which are meaningful only when attributed to the whole, not to its parts – e.g. the smell of ammonia”. Having indicated that OR functions within complexity, the question arises to what extent OR applications relate to emergent properties – in other words: How can emergence broaden OR's epistemology? What can be expected to emerge in an OR application and what are the benefits of such an emergence?

Complexity emerges as a result of the patterns of interaction between elements in a system (Cilliers 1998: p. 5). In an OR application (such as the facility location problem described earlier) the dynamic and non-linear interaction amongst elements may lead to a number of emergent properties. To start with, one would hope that after some time the interaction of elements will lead to an emergence of a better *understanding* of OR and the application. As time passes, stakeholders and communities may develop a *consciousness* of the application, its interaction with the environment and the consequences. The building of a warehouse in a specific region may impact on economic activities, which may lead to some form of competition amongst economic units that may ultimately change each of them into a better efficient and effective unit – thereby driving the overall economic structure or system to better *efficiency and effectiveness*. Other examples of properties that may emerge after some time may include operational changes (the way things are done), changes in social structures and the development of new eco-systems. Paul et al. (2014: p. 9) warn that the magnitude of an emergent property cannot be quantified. This is due to the open boundary and non-linear characteristics of a

complex system. This is also true in the case of an OR application as it is not possible to incorporate all elements that will interact or have an effect on the application. The non-linear interactions of elements in an OR system (e.g. a small model with a large economic or social impact) will make the quantification of emergent properties impossible.

6.2 Setting of boundaries

Other specific issues that need to be mentioned when dealing with complexity as an alternative epistemology are, firstly, the issue of boundaries that leads directly to the issue of knowledge. An OR application implies solving a specific real world problem. To solve such real world problems, the problem has to be framed in a specific way as it would be impossible to try and solve the problem by involving all of reality. Furthermore, for something to be recognisable as a system, it must be bounded in some way (Cilliers 2005a: p. 610). The OR specialist, together with a team of stakeholders, therefore needs to determine the extent of the system to be studied or modelled. The only way to achieve this is by setting boundaries, and according to Audouin et al. (2013: p. 12) “such boundaries, whether conceptual, spatial or temporal, for example, are essential as they enable the generation of knowledge”. Drawing boundaries, however, is not a simple straightforward exercise. Cilliers (2008: pp. 45-46) warns that closure by a boundary should not be over-emphasised, as one can never describe it objectively. According to him, a boundary should be thought of as something that *constitutes* that which is bounded – and not as something that separates one thing from another. A second point concerning boundaries raised by Cilliers is that a system should not be visualised as something contiguous in space but that parts of a system may exist in total different spatial locations. The idea of boundaries is not something new – not even in the OR discipline. The work of Midgeley et al. (1998) serves as an example of boundaries in an OR application. The new insights gained (or at least emphasised) through Complexity Theory on this point is that OR’s epistemology should accommodate (be broadened) the fact that boundary setting is artificial, not objective and temporary.

6.3 Lack of complete knowledge

Closely related to the issue of boundaries is the knowledge aspect. Cilliers (2008: p. 50) argues that to fully understand a complex system, one needs to understand all its complexity as well as the system’s complete environment. This is of course not possible and is the reason why boundary setting is necessary. The implication of this is that one can never have complete knowledge of a complex system, but only knowledge in terms of a certain framework. Cilliers further explains that the generation of knowledge in a complex system is an exploratory process and that the knowledge is always provisional. This seems to be important for OR applications – by accepting the boundary and knowledge principles of a complex system, the OR professional will remain aware of the existence of a diverse set of stakeholders and other elements that may impact the OR application while at the same time still setting boundaries to facilitate the practical problem and possible solutions.

The arguments concerning the provisional nature of knowledge in a “bounded” system may lead to a charge of relativism. This argument is rejected by Cilliers and others. Woermann (2010) pointed out that relativism (being relative to other things) only makes sense when it is contrasted with absolutism (standing in no relation to anything) – the fear of relativism is therefore something that haunts absolutism. Cilliers’s view is that “limited knowledge is not ‘any’ knowledge” (Cilliers 2005b: p. 260) and that complexity is not an excuse for relativism but rather a challenge to develop a new kind of scientific understanding which does not want to argue that “sloppy” work is acceptable (Cilliers 2007: p. 4).

6.4 Responsibility (ethics) for choices and consequences regarding definitions of boundaries

Another issue that flows from the concept of boundaries and provisional knowledge, is the idea of ethics, or – more specifically in this case – responsibility. When a specific framework is chosen (boundary setting) to investigate and interpret an application area or system, one cannot escape from the fact that the complexity of the system has been reduced and that a certain level of uncertainty in knowledge will prevail. Cilliers (2008: p. 52) warns that as a result of such a boundary setting, one cannot blame the outcomes of decisions and actions on such a procedure and that responsibility should be assumed. Woermann (nd: p. 7) confirms this by stating: “If our models do not correspond with reality (due to boundaries – my text), and if they are the outcomes of certain choices, then we must also take responsibility for both the intended and unintended consequences.” Similarly, Audouin et al. (2013: p. 3) note that boundary definitions involve choices that are essentially value-based. Ethics and ethical considerations are seemingly important in Complexity Theory and more insight from a philosophical viewpoint on ethics and complexity can be found in Woermann and Cilliers (2012). The idea of ethical considerations and responsibility in OR is widely accepted. Examples of an awareness of this can be found in Ackoff (1974) and Gallo (2004). Both these studies focus on responsibility, with the latter concentrating on not just responsibility towards an OR client but also to a wider audience (e.g. stakeholders, society, nature) that may be directly or indirectly affected by the results of an OR application.

A facility location problem was earlier described as a typical example of an OR problem to illustrate the implications of complexity thinking for OR. Given the four characterising aspects of complexity (sections 6.1–6.4), it is fairly easy to quote other well-known classical OR problems to serve as further concrete examples of how OR could be influenced by applying a complexity lens to them. For example, the portfolio selection problem is a fundamental OR model in modern finance that can be solved with a standard non-linear mathematical program. The problem entails the selection of a set of stocks given a limited budget and subject to a certain level of risk and/or an expected return of the chosen portfolio. The well-known data envelopment analysis problems where the efficiency of a set of homogeneous decision making units (e.g. bank branches) are evaluated based on input and output

variables represents another practical example. A third example may be found in the area of manufacturing applications – e.g. a standard production mix problem. These types of problems use linear programming models to help plan the optimal mix of different products to be manufactured subject to resource constraints. There are also many other standard OR problems in a wide variety of application areas that could be cited as examples for this discussion.

If one considers the three examples above from a complexity perspective it becomes clear that the majority of conventional OR problems should not simply be treated as a mathematical model that seeks an optimal answer while neglecting the characteristics and associated intricacies of insights offered by complexity theory. All three examples are related to economic applications where a large number of elements continuously interact. The nature of this interaction is non-linear as a small change in one of the elements may lead to large changes in the application area. The interaction will no doubt lead to emergent properties (e.g. learning and deeper understanding of the problem) that may change or render initial solutions less useful. To model the three problems it is clear that each one will have to be framed to a certain extent to be able to solve the problem – this means that artificial boundaries will have to be set and defined. Owing to these boundaries the solutions and knowledge offered by the OR models are only conditional as the impact and consequences of the application cannot be fully known. E.g. the consequences of a specific financial portfolio, a specific product mix or a recommendation on the efficiency or inefficiency of a decision making unit may be far reaching once the OR solutions are implemented. Finally, the consequences and lack of complete knowledge will result in ethical responsibilities for each of the three applications. This ethical responsibility is applicable to both the OR specialist (whose models recommend a financial portfolio, a product mix or a recommendation on the efficiency or inefficiency of a business unit) and the OR client for implementing the OR recommendations with the associated consequences for humans, the environment, society etc.

In general the characteristics, which are prerequisites for complexity, are to a large extent present in the context of OR applications. The non-linear interactions of elements in an OR application will lead to emergent properties, such as a deeper understanding and consciousness of the problem and its consequences. The setting of boundaries forms part of any OR application and is necessary to properly frame a problem in order to produce possible solutions. Furthermore, there is an increasing acknowledgement in OR that knowledge produced through the setting of boundaries is only provisional – a complete OR application with its impact and consequences cannot be fully known. Lastly, the issue of boundaries and the associated lack of complete knowledge emphasise and broaden the ethical responsibility of OR.

The acknowledgement of the above complex aspects in OR, and the alignment of OR's epistemology to complexity theory, could help to develop new methods for modelling decision making. This

acknowledgement that decision making happens in a complex reality, furthermore makes OR more prone to the benefits other disciplines experienced through their link with complexity. For example, OR should also be *less concerned with predicting results and more concerned with the process* (this will enable OR to take into account other stakeholders, society, nature, etc.); *be taught more effectively* (i.e. a greater sensitivity for setting boundaries and ethical implications); *understand change better* (also initiate change and a willingness to adapt models and methodologies); *make sense of the dynamics of emergence* (i.e. expect any unexpected emergent properties); and *assist with the explanation of the different properties of decision-making and building multi-level representations of the world*. The aspect of “building multi-level representations of the world” is of specific importance in the context of this paper’s argument. While OR is generally and historically more aligned to a positivistic (reductive scientific) epistemology, its strong link to complexity (as shown in this paper) opens up an acknowledgement to a more “open” epistemology, and this leads to the possibility of this multi-level understanding of the world in which it operates. This may bring new fundamental insights into the discipline of OR and new directions of understanding the basic principles of OR as described above.

The acceptance of complexity and complexity principles as a framework for understanding (epistemology) or changing the way one thinks about applications or systems like OR is not free from criticism. Some examples of challenges to Complexity Theory are highlighted in the work of Morrison (2006: pp. 6-10), who raised some of the difficulties of Complexity Theory in education. The issues raised are, however, generally applicable and not limited to the area of education (and therefore relevant for OR as well).

One of the first issues raised is that of how novel a theory Complexity Theory really is. Concepts such as the ten characteristics used to describe complexity are not new and may simply be a reformulation of known aspects. In addition, it may also appear as if complexity is simply a statement of the obvious (using old concepts). Morrison also asks questions about the usefulness of Complexity Theory – it is mainly regarded as a post hoc explanation with limited prospective or predictive utility. It also has the disadvantage of being non-optimal, non-controllable, non-understandable and non-immediate. These characteristics do not fit with systems, applications or practical situations that seek efficiency, control, comprehensibility and immediate solutions. It also raises further questions on responsibility: for example, if one cannot predict the consequences of one’s actions, in what sense can one then be held responsible for what happens after one’s actions? These criticisms should be taken into account when dealing with OR in the context of complexity because it can further enrich the new directions OR may follow.

7. Conclusion

To conclude, it appears that applications of OR function in the same structure and topology of a complex system and that it is not solely based on the objects that it comprises. This, however, does not imply an argument against mathematical modelling techniques – models have to be built to understand problems or applications. But, as Cilliers puts it, “it is an argument that models of complex systems will always be flawed in principle and that we have to acknowledge these limitations” (Cilliers 2008: p. 49). Complexity Theory therefore provides a new and different theoretical framework and epistemology with important implications for the way in which OR and OR applications *should be understood*. It specifically addresses the failure of traditional reductionist approaches and the concerns of Ackoff. As stated above, it is clear that while OR is generally and historically more aligned to a modernistic (reductive scientific) epistemology, its strong link to complexity opens up an acknowledgement to a more open epistemology which leads to the possibility of a multi-level understanding of the world in which it operates. This acknowledgement may further open up new prospective and transdisciplinary interaction for OR in a more sustainable and ethical way. It is important that OR applications are not just treated as a “hard” science but that OR specialists realise that “science without philosophy is blind, and philosophy without science is paralysed” (Cilliers 1998: p. 13). When one acknowledges that OR based decision making happens in a complex world, and verifies the complexity of structures and environments in which OR approaches are applied, new contributions can be made to the epistemology that fundamentally informs the field of OR.

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CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

1. Purpose of the study and conclusions

The purpose of the research was to investigate the relations between the epistemologies of Operations Research (OR) and Complexity Theory. The aim was to determine what new insights into OR's epistemology can be derived from comparing the two disciplines. To address this problem, the study proceeded as follows.

A brief introduction of both OR and Complexity Theory was presented. It was then shown how a typical OR application can be described in terms of the characteristics of a complex system. Next, the general reductionist epistemology of OR as well as the more postmodernist epistemology of a complex system were presented. It was argued that although OR is still inspired by a mechanistic framework or approach; it functions within a context which exhibits complexity characteristics and properties.

The study concluded that all aspects which are in general prerequisites for something to be identified as complex, are to a large extent present in the context of a typical OR application. These aspects include the general characteristics identified in the literature as well as other properties such as emergence, boundary setting, lack of complete knowledge and ethics. In addition to this, it was also noted that, through the acknowledgement of complexity principles, OR's epistemology may benefit in the same way other disciplines had benefitted from such an acknowledgement. The implication is therefore that Complexity Theory provides a new and different theoretical framework with important implications for the way in which OR's epistemology and OR applications should be understood. This framework addresses the traditional reductionist approach and may lead to a more "open" epistemology with new prospective and transdisciplinary interactions for OR in a more sustainable and ethical way.

2. Limitations of the research

An obvious limitation of this study is that it explored only Complexity Theory as a new framework for gaining insight into the OR discipline. The field of Chaos Theory (which was excluded in this study) is very closely related to Complexity Theory and the two fields share certain concepts and definitions, for instance the concept of self-organisation. The study further excluded work that has been done in the area of systems thinking, which will no doubt also offer new opportunities for understanding OR.

3. Contributions of the study

The first contribution of the study is to provide a new perspective on the OR methodology or epistemology in general. Existing methodological problems (as listed by Ackoff) and the general reductionist epistemology of OR were highlighted, leading to the conclusion that OR still operates mainly in a paradigm of order where it is assumed that all phenomena are context-free and can be explained by reducing a system to its parts.

Secondly, the study contributes by showing that a typical OR application can be described in terms of the characteristics of a complex system. Furthermore, such a typical OR application context also exhibits other properties of complexity, such as emergence, boundaries, lack of complete knowledge and ethical consequences. This emphasises the epistemological tension in OR and makes it necessary to acknowledge that the ambivalence of OR's epistemology seems to be driven towards the more "disorderly, complex and open" epistemology.

Thirdly, it contributes by indicating the consistency between findings of previous studies where the existence and value of Complexity Theory were acknowledged, and where similar benefits (e.g. deeper understanding and new insights) became possible for OR.

Finally, the study provides an alternative theoretical framework with important implications for how OR's epistemology and OR applications should be understood. It opens up an acknowledgement of a more "open" epistemology, which will hopefully lead to a new multi-level understanding (epistemology) of the world in which OR operates.

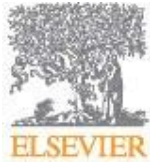
4. Recommendations for future research

Consistent with the limitations of the study outlined earlier, further research can be done on the following.

- Exploring the influence of other paradigms such as Chaos Theory and Systems Thinking. Other recent trends, such as Big Data, may also play a significant role in the approaches and methodologies of OR.
- Ethical aspects, and particularly the question of responsibility with regard to the principles of Complexity Theory, may be helpful to broaden the research on OR as a complex system.

APPENDIX

Prescriptions for a research article submitted to the *European Journal of Operational Research*



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