SYSTEMS ANALYSIS AND MODELING IN TRANSDISCIPLINARY RESEARCH

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Contents

Summary

Transdisciplinary research (TR) represents a novel challenge for science. In contrast to traditional disciplinary research or interdisciplinary efforts of the last decades, e.g., in molecular genetics, it is concerned with subjects raised by everyday life which cannot be considered in an laboratory-like setting, separating scientists from their object of investigation. TR generates knowledge about processes, valuations and strategies to mitigate negatively-valued developments and improve societal practices, taking into account the needs and interests of various stakeholders. The issue of Sustainable Development is the most prominent example of this kind of subject. Many of the problems raised are highly complex and thus require non-traditional methods of analysis, necessarily bridging the gaps between different scientific disciplines and between science and societal decision-making. Systems Analysis and Computer Modeling are at the very forefront of these methods, which, however, raise some major epistemological problems.

Systems Analysis aims at the identification of the major elements and the interactions determining the broader subject one is interested in. We have to distinguish between a static analysis, which concentrates on the pure analysis of the interacting elements, and is thus concerned with the issue of systems definition and encapsulation, i.e. what is

assumed to belong to the systems and what is left out. In a second step this analysis is extended to capture so-called dynamic systems, as well known, e.g., from classical mechanics in physics. Here it has to be clarified how the elements interact and how this interaction determines the system's dynamics. In general, this last step is already closely related to the field of modeling. Nevertheless, one can use these preliminary steps of systems analysis to structure the problems on hand, e.g. which problems are connected, how do problems overlap, which appear to be more central than others, what actually is a problem and what constitutes it as such, etc.

"Modeling" should always be considered in close relation to systems analysis. As a matter of fact the latter can be considered as the first phase of any modeling exercise in which a *mental model* of the interesting part of the world is outlined. Within a second phase this "word model" has to be formalized in terms of mathematical terms, e.g. differential equations, difference equations, optimization problems, etc. Finally, in most cases the formalized model is implemented on a computer using methods of numerical mathematics, artificial intelligence or symbol manipulations. With respect to model applications for decision making and in transdisciplinary research it has turned out to be of highest priority to include stakeholders right from the outset, e.g. already in the phase of mental modeling. This is necessary to ensure a sufficient level of problem orientation, e.g. by including the model variables stakeholders actually are interested in, or the control variables to which potential model users, e.g. all kinds of societal decision makers have access.

There are a number of applications for modeling and systems analysis in policy advice and decision making. Most prominent is the field of anthropogenic climate change, i.e. the increased greenhouse effect induced by human activities, particularly by fossil fuel burning for energy production. This example shows the different types of how policy can be influenced by science: (a) in the identification of a potential problem and growth of problem awareness, (b) in strategy development to solve the problem. Whereas the first has been a historical process, the second has been experienced within a few concrete exercises, e.g. the Delft process in The Netherlands/European Union. It has become evident that though models can be used in policy-making; there are major limitations due to, e.g., model credibility, model uncertainties, complexity and intransparence etc. It turned out, e.g., that structurally simple models are often more useful in policy making than highly complex, integrated models.

1. Introduction

Transdisciplinary research (TR) aims at providing knowledge on those issues to be managed in society which encompass complex internal interdependencies on the one hand and various levels of societal decision making on the other. TR therefore addresses knowledge about processes, valuations and strategies, taking into account needs and interests of various stakeholders (see *Methodology of Transdisciplinary Research*). To begin with, "complex" indicates a high degree of mutual dependency between different elements related to the problem on hand, often across the causal models of the disciplines. Examples comprise anthropogenic climate change in its whole range of causes (e.g. energy needs and means of production), climate dynamics (including atmospheric, oceanographic and biospheric processes), and consequences (e.g. impacts of climate change on ecosystems and human societies). In recent years analyses on the various feedback loops between the "system's components" have revealed a significant potential for surprises within the Earth's climate, i.e. switches and jumps with rapid changes in regional or even global climate. It is, for example, expected that global warming will lead to an intensification of the global water cycle with more intense rainfall, in particular in the higher latitudes. This might eventually induce a switch-off of the North-Atlantic deep-water formation, i.e. the process which brings warm water from the tropics to the north Atlantic, thus inducing a rather temperate climate in northern and central Europe. In general these investigations have proven the need for transdisciplinary research to focus complexity as the most relevant of its ingredients.

Besides complexity, another major stumbling block for any transdisciplinary effort arises from uncertainties. Knowledge on the different processes, facts, or data is very often vague, incomplete, or uncertain. Within complex systems these uncertainties can explode, i.e. no real prediction would be possible, as the error bars would grow exponentially. This case applies, e.g., within chaotic dynamic systems (Schuster 1989), where a small deviation in the initial conditions grows exponentially in time, i.e. a possibly small uncertainty is blown up. One major implication of uncertainties is the intractability of *predictions* in the strong sense, i.e. of giving a statement about a single future. This task should be left to soothsayers but science should keep its hands off it. The least it should do, however, is to make its assumptions explicit and to investigate the logical implications of these assumptions – and that is the major goal of modeling and systems analysis. In other words: complexity and uncertainties urge us to be modest about our models, their usage and applicability.

Finally the issues of transdisciplinary research are embedded into dynamic processes, rather than merely representing static snapshots. Dynamics is induced on the one hand by the interactions themselves, but also by singular perturbations, e.g. fires or storms in the case of ecosystems or wars and revolutions in the case of human systems. It is dynamic evolution which brings about the problems actually to be tackled with TR – and it is dynamic evolution which eventually lets them disappear again. Within Earth System Analysis, the major question is: how can the evolution of natural and human systems on a global scale be influenced, managed or controlled in order to achieve goals set within a societal dialogue – for example with respect to sustainable development (Schellnhuber 1998).

These three properties of the issues, i.e. complexity, uncertainties, and dynamics, can best be addressed by application of systems analysis and modeling. These basic tools help to frame and systemize the discussion of the issues, to study assumptions explicitly and to test political options and strategies.

2. Systems Analysis

Systems Analysis is the general headline for the investigation and analysis of a well-defined – in particular with respect to the borders of the system, i.e. what does belong to it and what does not – assembly of issues and their mutual interdependency. It breaks down into a static and a dynamic part and is often not clearly distinguishable from modeling. Without modeling, the main achievement of systems analysis within TR is the identification and systematization of the problem, its components and building blocks.

2.1. Static Analysis

Within the first step of the analysis one identifies the major building blocks of the system and thus defines the *system*. This analysis requires a careful *differentiation* of the problem at hand, i.e. a line has to be drawn between the inside and outside of the system differentiating between those aspects which play a significant role and those which do not. The second basic problem of systems analysis refers to the *internal* differentiation of the system into individual components or elements and their interaction. This is called the *structure of the system.* There are various ways to actually carry out and support this task, e.g. statistical analyses, theoretical considerations, expert elicitation or "educated guess". It has to be underlined that a priori this differentiation often cannot be justified rigorously and that it is also dependent on the question raised. In many cases it has to be proven by its usefulness in supporting transdisciplinary research: does it help in explaining and resolving the problems and issues in question? Is it applicable within the decision making process? Etc.

Against this background it has become evident that the "openness" in defining the system's internal structure and its external boundaries is actually helpful and valuable for transdisciplinary research. On the one hand the stakeholder or decision maker concerned with the problem analyzed might be considered as external to its decision making process. The implications of the actions taken, however, can only be assessed if these actions *are* included in the system, i.e. the system's border runs between the stakeholder's action and his decision making process.

Secondly, the internal differentiation might ideally reveal observables and indicators accessible and useful to the user of the analysis (and later the model). Both issues imply that within a counseling and product-oriented project (see *Methodology of Transdisciplinary Research*). Stakeholders and decision makers have to get involved from the very first stage of systems analysis. This ideal situation might, however, not always be feasible in a highly coupled system, e.g. if the decision making process itself is an indispensable part of the problem.

Formal analysis of the structures of static systems can help us to understand implications of complex networks of relations. In principle the steps required for this type of analysis are the same as for dynamic systems and belong to the realm of modeling (see below).

2.2. Systems Dynamics

Its procedural character is a major reason to use transdisciplinary research for resolving the problems of development and environmental degradation. Some of the impacts of actions often occur with a long time delay, in some cases like anthropogenic climate change even generations ahead. Generally, due to the complex character of the problems at hand the impacts happen over a whole range of time horizons, with different intensities and, in spatially extended systems, in different locations. This induces subtle problems in decision-making and its scientific analysis, for example that conventional discounting would let almost any kind of impact disappear which might occur more than a hundred years ahead.

Without specifically looking at these problems, however, the dynamic character actually requires that we investigate how systems behave in time. To this end it appears to be necessary to distinguish between the dynamics of the internal variables, i.e. differentiate whether changes of the entire structure of the system occur, including its interactions and boundaries, or whether this is not the case. Examples for the latter type of transitions are political changes from a dictatorship to a democracy. These kinds of transitions appear to be much harder to analyze than the first kind of dynamic and only a few formal approaches exist, e.g. evolutionary theory, modeling and algorithms. Conventionally, the notion of systems dynamics is restricted to the first type of changes, introduced by Jay W. Forrester in his famous book *Industrial Dynamics* (Forrester 1961).

From the structural point of view the main reason for systems dynamics of the first kind is induced by *feedback loops*, e.g. X acts on Y, Y on Z and Z again on X. Feedback implies that it is necessary to study the whole system in order to understand the behavior of X (or Y or Z), i.e. of each of its single components. Vice versa, any action from outside of the system that changes an individual component carries through the system and induces changes in every other component. How these changes are carried through can best be studied by the use of computer modeling, which, however, is not restricted to issues of systems dynamics.

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Biographical Sketch

Gerhard Petschel-Held* received his Ph.D. from the University of Frankfurt/Main, Germany in 1992 with a thesis on quantum mechanical fingerprints of classically chaotic systems. Since 1993 he was with the Potsdam Institute for Climate Impact Research, Germany where he was acting head of the Department for Integrated Systems Analysis. His major field of work was the development of the so-called syndromes concept for analyzing global environmental change. Within the approach, the richness of local changes embedded into global change is categorized into typical patterns. Gerhard was leading the "syndrome-team" at PIK since its very beginning. He was also involved into other attempts of integrated analysis of global change, e.g. the ICLIPS approach of inverse modeling, and servee as a coordinating lead author of the Millennium Ecosystem Assessment. He has published more than 50 articles on global change, concepts of modeling, and dynamical non-linear systems. He died in 2005.