On the Influence of System-Dynamics-Based Modelling on Sustainability Discourse – Relevance Today

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Abstract

The report to the Club of Rome on the “Limits to Growth” was issued in the year 1972. The modelling work underlying the warnings and recommendations in the report were produced using the System Dynamics “philosophy”, e.g. a specific view on how to analyse system structures, how to apply scenario methodology to global environmental problems, and a technical tool to unveil the dynamics of the system behaviour.

The report was extremely influential on early environmental discussions and establishing an ecological movement in the 1970ies. Later on, revised versions of the model were published in 1992 and 2004, the earlier one under the title “Beyond the Limits”. Several events are organized in 2012 to celebrate the 40 years period of influence of the reports.

In my opinion there are two aspects with which their influence can be described. Firstly, there is the System Dynamics machinery itself. Thinking in feedback loops, positive and negative circles, different types of dynamics (changing from growth periods to stabilized stages), considering the interplay of sub-systems in order to show the general system behaviour, are nowadays proven elements in several system studies, like the Syndroms approach and numerous environmental simulation studies.

Secondly, the involvement of stakeholders is another important aspect. Dana and Dennis Meadows, the main authors of the studies mentioned, attached great importance to team working in interpreting results and distributing knowledge about the system behaviour. Shortly after having published the reports they started to organize meetings with decision makers, opinion leaders, and affected people to discuss results and consequences and give support to a dissemination of their insights.

1. Problem Setting

There are numerous approaches in Informatics giving support to the understanding and treatment of environmental problems. The series of EnviroInfo conferences with all their contents surely verifies that (may be quit “natural”) statement. Beside all the data base approaches, geographical information systems, remote sensing, measurement techniques, communication networks, etc., there is an additional field of important activities: simulation approaches.

Due to the specific nature of environmental (and sustainability oriented) research from the very beginning interdisciplinary and integrated approaches have been followed. Therefore, a profound basis for modelling and systems analysis on these issues is at hand and the experiences made there are helpful to give our own approach contours. However, an immense number of studies and publications with different suggestions for structuring information are available.

Considering sustainability issues there is one crucial characteristic that requests support by simulation methods, that is the interplay of different in themselves dynamic components or sub-systems, and especially the delays interfering with these dynamics. If the problems are of that kind complex systems are the object of analysis. As has been mentioned a couple of years ago, these complex systems often show “counter intuitive behaviour” (Forrester). Measures activated in order to solve problems lead, under some

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circumstances, to a more aggravated situation, or, sometimes, a worsening of the situation has to be accepted before later on the desired effect will turn up.

The most influential modelling paradigm to deal with that kind of problems was System Dynamics, introduced by MIT professor Jay Forrester in the 1960ies. Forrester’s connection to the founding and development of Cybernetics as a scientific discipline is not well documented. However, he undoubtedly is responsible for important extensions to the framework especially in providing crucial features for analyzing transformation processes. And he also contributed to the development of Sociocybernetics, that is, the inclusion of actors and the addressing social questions. From the very beginning Forrester worked about social problems: development of inner-city areas of US-American agglomerations. That was a sound basis on which Meadows et al. build their modelling experiments addressing environmental and sustainability-oriented issues.

2. System Dynamics as Modelling Paradigm

The modelling approach – a methodology comprising a modelling paradigm, a software instrument, and set of typical problems - was explained in two books by Forrester: “Industrial Dynamics” and “Principles of Systems” (Forrester 1972).

![System dynamics steps from problem symptoms to improvement](Source: Forrester 1994)

There, the idea of a primacy of structural relationships over concrete data was laid down. The existence of positive and negative feedback loops in systems was identified as the main drivers for the dynamics of systems, but also for qualitative characteristics like stability, direction of evolutionary change, or periods of decline.

In “Principles of Systems” Forrester formulated these insights as a hierarchy of components:

I. The (causally-) closed system whose behaviour is determined from within the system boundary without external influences.
   A. Feedback loops as the basic elements systems are composed of.
      1. System states are the essential variables in those feedback loops.
      2. Rates (or decision rules) as a second essential type of basic variables in a feedback loop.
         a) A goal the process tends towards.
         b) An observed system state that is contrasted with those goals.
c) A mismatch between a goal and the observed system states.
d) A decision resulting from those mismatches (discrepancies).

The modelling activity was conceptualized from the very beginning as an iterative process (Fig. 1). Phases (steps) of model construction and simulation are followed by dissemination and discussion steps – results, eventually, are fed back to change the model if needed.

Forrester developed – applying the modelling paradigm - a first “world model” (a first sketch on a paper napkin during a flight back from Europe) and carried out computer simulation runs to detect the consequences laid down in the essential structures of the world system.

Another import step done by Dana and Dennis Meadows was applying the methodology to the world problématique on a more detailed level. That was the famous report to the Club of Rome.

The Meadows refined the model and added a lot of model variables to allow for establishing interfaces with real world data and statistics. The structural kernel of the model is shown in Fig 2. The main compartments of the system are identified as: population, industrial capital, agricultural capital, service capital, and non-renewable resources.

Fig. 3 shows the more detailed model of the “non-renewable resource sector” in the older notation of DYNAMO, the software package used at the time of the early computer experiments with the world model. The industrial capital stock is altered by investment and deterioration rates. These rates are themselves influenced by a lot of other model variables like, beside others, the amount of consumers in the system and a certain level of life quality (demand). Industrial capital is of influence on the stock of non-renewable resources, moderated by variables like “industrial output per capita” and an indicator representing the resource usage efficiency. Model experiences then uncover the dynamics inherent in the model structures, for example, the behaviour of the system, when the initial level of non-renewable resources is doubled compared to the level used in the standard run of the world model. Due to the feedback loops and
exponential growth triggered by these loops the system breakdown still occurs, only a few years later as with half of the resources available.

Figure 3:
Well-known simulation results: the Standard Run
Source: Meadows 2004

Figure 4:
Flow diagram for the non-renewable resource sector
Source: Meadows 1974, 399
It is the dependence of the quantitative outcomes on the feedback loop networks that makes the experiments with the models so interesting and their results, often, astonishing. The exponential dynamics (as shown in the consequences for the main components of the “world system” in Fig. 4) produces results hardly to be foreseen without computer simulation and deep analysis of model structures.

Often the Meadows approach was misunderstood as a prognosis about what will really happen in the future. Far away from such an interpretation, the Meadows insist on the openness of the future and a relevant part of their analyses comprises scenario experiments about “breaking the trends”. The dynamical nature is obvious when different points in time are considered where measures are taken to change the system towards a more sustainable future. The experiments show that twenty years of idleness cause an increase in the severity of problems (Fig. 5). Measures put into practice in the 1980ies would have more easily let to a sustainable future than those taken 20 or 30 years later. And due to that idleness Meadows could talk about the fact that nowadays the option “sustainability” is not a realistic one, any longer (Meadows 2000). Needless to say, it is not meant that mankind cannot survive – however, the standards of living may be much lower than today in the decline phases after the year 2035.

There is an interesting side aspect considering the model experiments with the world model. Meadows decided rather early to not investing time in a further improvement of the model, e.g. to expand the number of variables like that was done by Pestel and Mesarovic in their modelling project of a multi-level world model. Instead of working on such extensions, Meadows decided to use the model in workshops and participatory activities, in order to confront decision-makers with the consequences of the simulation runs. For him, those interactions with people who can have some influences on future developments seem to be of higher concern as making the models bigger and bigger.

Figure 5:
Time dependency of successful solutions
Source: Meadows 2004
On the occasion of the 40 year anniversary of the first publication of the “Limits” a critical analysis of the simulation results was undertaken. Figure 6 shows a comparison of the so-called “standard run” of the “Limits to Growth” with empirical data. Considering the data, Turner concluded as follows: “The data review continues to confirm that the standard run scenario represents real-world outcomes considerably well. This scenario results in collapse of the global economy and population in the near future. It begins in about 2015 with industrial output per capita falling precipitously, followed by food and services. Consequently, death rates increase from about 2020 and population falls from about 2030 – as death rates overtake birth rates.” (Turner 2012, 123)

3. Refinement: Multilevel Approaches

A harsh criticism of the Meadows model points to the fact that the world is seen as an undifferentiated, unique object where all regional particularities and characteristics are equalized and hidden. The argument states that there is not this unique world so that it is not of much worth when the differences and inequalities are ignored, especially for recommending actions.

At that point the approach named after Eduard Pestel and Mihajlo Mesarovic comes into play. The concept of world modelling is based there on the idea of several distinct world regions and “strata” which describe different layers of events and activities within those systems. The approach was developed under the label “hierarchical and multilevel systems theory” and used for several system studies on global but also national development (for example, the “Deutschland-Modell”). The standard scheme differentiates between a causal stratum (the energy and material fluxes are located at that level), a decision stratum (where technological and economic decisions are made that influence the causal stratum), and a norms stratum (where longer lasting norms and values are located that guide – to a certain extend – the decisions made). The different strata are associated with different time constants: on the causal stratum changes are occurring from one moment to the other, decisions are made from day to day, whereas norms do not

![Figure 6: Comparison of historical data with three Limits to Growth scenarios, for economy output variables: industrial output per capita](source: Turner 2012)
change sometimes for a certain period of time, until problems cannot be any longer solved on the basis of these norms. Then, also the norms can be a subject to changes.

These different time constants were used by Hartmut Bossel to model structural changes in the world energy system. Bossel was a member of the research team active with the Mesarovic-Pestel-World-Model. Modelling the energy sector he wonders how to deal with possible (and probable?) system changes. He used a hierarchy of normative concepts (attitudes, values, norms) and discusses how conflicts between elements on one (lower) level might determine the selection of alternatives that omit those conflicts. The idea is to climb on in the hierarchy until a value concept is found that is undisputed (like a superior value “survival”). Starting from this concept a new branch in the values hierarchy is analysed with respect to an acceptable problem solution.

Another global modelling approach of some influence was the GLOBUS project (Bremer 1987). An alternative approach was the so-called Bariloche Model (Herrera/Scolnik 1977) in which the interrelationships were reduced to a hierarchical order of necessary actions, necessary for solving the problems of mankind. Today, that type of analysis would be subsumed under the headline “sustainable development”. Thus, a broad variety of applications can be found all of them relying by some means or other on the formulation of interrelationships between components representing problem constellation or systems. However, the approach also has its limits, e.g. in systems that show chaotic behaviour.

Recent model experiments in the context of global change problems are using the so-called “Syndroms Approach” (Schellnhuber 1997). Similar to former model studies a set of compartments was identified that play a role in the occurrence and solution of global environmental problems. With the concept “syndrome” “archetypical patterns of civilization-nature-interactions, which can be understood from the methodological point of view also as sub-dynamics of Global Change“ (Schellnhuber 1997).

Figure 7: Basic structure of the Green Revolution Syndrome
Source: Schellnhuber 1997
The compartments generally used are: Biosphere, Atmosphere, Hydrosphere, Population, Pedosphere, Economy, Psychological Sphere, Social Organization, and Science/Technology (see Fig. 7). Compared to the Meadows model the resources sector is described with more detail and the role of decisions is included explicitly.

The approach builds on the hypotheses that different problem types (syndromes) are inscribing different structures in the realm of the compartments identified and are connecting several variables in the compartments to variables in other compartments (Fig. 7 - with a display of the so-called Green Revolution Syndrom). Intensive empirical research was carried out to fill in data and particular information about the problem constellations.

An interesting aspect is the specific technique that is used to analyse the dynamics on grounds of the structural relationships. In contrast to most of the other approaches described above the importance of qualitative information is maintained. In other words, a simulation technique was developed making direct use of qualitative information. Thus, the usual simulation technique on the basis of differential (difference) equations and associated mathematics (like integral calculus) was not applicable. An alternative was found in artificial intelligence research with “qualitative reasoning” and “qualitative simulation” techniques (Kuipers 1994). With these techniques knowledge based systems, that are static in principle, got a dynamic supplement. The development of a variable during the course of time is represented by certain “landmarks”, that are especially – from a dynamic point of view – those points where the direction of development changes (the growth process comes to an end; exponential growth continues; stability is maintained). Problematic are those points at which several influences stay in conflict, for example, when both an increasing and a decreasing process meet. In a qualitative “calculation” nothing can be said about which of the two processes dominates. Therefore, several cases must be considered in the course of development.

![Figure 8](image)

**Figure 8**

basic system structure used by Randers

*Source: Randers 2012, 57*
4. **Current Application**

Jorgen Randers, one of the authors of the original work on the Limits to Growth, published a book with the title: *2052 – A Global Forecast for the Next Forty Years* (Randers 2012). In contrast to the “Limits” he aims at foreseeing some of the forthcoming strands of future developments. Again a basic set of interrelationships is guiding his analyses, similar to the world modelling basic structure (Fig. 8). Because of the relevance of the conclusions, Randers’s statements about the present relevance of the Limits to Growth (LtG) are presented as a résumé as follows:

“First, LtG points to the urgent need to develop “one planet living”. If humanity wants to become sustainable, it is a fact that humanity must organize its ways in a manner which fits within the physical limitations of Planet Earth. (…).

Second, there is need for contraction of the human ecological footprint. (…)

Third, we have to avoid further decision delays in the global effort to stop growth in, and actually start reduction of, the human ecological footprint. The most obvious need is for clear willingness to act now, even if the benefits won’t be reliably observable before a generation hence. Humanity must agree on investment in new climate-friendly solutions before they are commercially profitable.

Fourth, limits appear surprisingly fast if growth is exponential. (…).

Fifth, LtG points to the need for a solution to the three fundamental and legitimate problems poverty, unemployment, and old age insecurity that underlie the global fascination with growth. (…).

Sixth, at the deepest level, LtG reminds us that the ultimate goal is well-being, not growth. Economic growth evolved as a tool to increase human consumption and well-being. Population growth is a result of the human success in improving its material standard of living. If continuation of these types of growth no longer increases human well-being, the logical move is to drop physical growth and seek well-being.” (Randers 2012)

5. **Relevance for SEIS**

In a document introducing the Shared Environmental Information System the Commission describes the aim of the endeavour as follows: “Timely, relevant and reliable information on the environment is absolutely necessary for decision makers to respond to the environmental problems of our time. But this is not enough. Our citizens are also entitled to know if the quality of air and water in their neighbourhood is good enough or if floods, droughts or pollution is risking their property and livelihood. This is the reason we must improve further the way we collect, analyse and communicate information on our environment.”

Reconsidering the System Dynamics approach there are at least two important aspects that are of importance for a shard information space. The first aspect is on models as a methodological tool to allow for a better understanding of the problems tackled. With System Dynamics a mid- to long-term perspective comes into play that is essential for comprehending sustainability related issues. And furthermore, if relationships between different sectors are drawn together on the level of a meta-model knowledge from different sources can be integrated and communicated properly. Thus, in the face of the often overwhelming complexity of sustainability related real-world problems researchers and decision-makers are able to interpret consequences (with respect to dynamics) and show clearly the holistic aspects of the problem issue when supported by such a meta-model framework.

There is another lecture learned from the model experiments dealing with the “world problematique”. At a certain point in the development and application of these complex models it is necessary to include people from outside the researchers community. Stakeholders, decision-makers, politicians, planners, interested laymen should be invited to discuss models, simulation results, and consequences in an iterative modelling process.
Bibliography


schaft (in German only)


Some of the material has been already published in