Theory-Building with System Dynamics: Principles and Practices

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Abstract. System Dynamics is a discipline for the modeling, simulation and control of complex dynamic systems. In this contribution, the methodology of System Dynamics-based modeling is argued to be a powerful and rigorous approach to theory-building. The strength of the pertinent process of theory development lies in its high standards for model validation, and in a combination of abductive reasoning with induction and deduction. The argument of the paper is underpinned by an application of System Dynamics to the elaboration of a theory in the new field of Cultural Dynamics.

1 Introduction: Theory-Building in Perspective

Theory-building, in principle, is more than an exercise in academic abstractions. It is an activity fundamental to the survival of societies, organizations and even individuals. Constructing a model, in the sense in which it is used here, consists in building and mathematically formalizing a theory in order to orientate action. It is a device for coping with whatever is complex. As complexity in our time tends to be of a high degree, and often growing, the quest for better theories is a necessity for both academics and practitioners.

Essentially, three different modes of scientific inquiry can be distinguished, namely, deductive, inductive, and abductive [13]. Adopting a deductive research approach entails concluding upon a particular statement derived from theories or laws considered to be universal truths, whereas inductive inquiry involves deriving universal theories or laws from particular observations. Finally, by researching in the abductive mode, possible explanations or interpretations of observed facts are provided, i.e., one generates an understanding of the fundamental driving forces and structures of the phenomenon under consideration. Characteristic outcomes of abductive reasoning are explanatory principles and theories obtained by looking beyond the facts observed in similar cases,thereby taking the longest step of all three modes of scientific inquiry towards the generation of new knowledge. In order to overcome the limitations of each approach, researchers have tried to combine the different modes of theory-building. This is often found to be difficult, or biased in one direction or the other. Hence, there is a need for rigorous theory-building approaches which balance out the trade-off between the quests for genuinely new insights, conceptual stringency, and empirical soundness.

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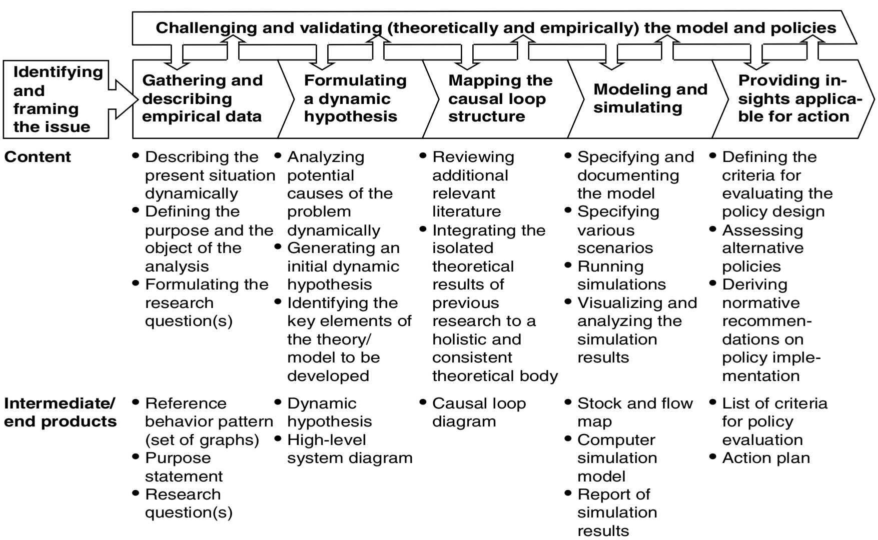
In this contribution it is demonstrated that the methodology of System Dynamics offers a particularly powerful process and technique for effective theory-building in order to improve decision-making in the context of organizations and society. This methodology is designed to achieve an understanding of the fundamental driving forces and structures underlying a problematic mode of behavior, as well as conceptual and empirical rigor.

2 Theory-Building with System Dynamics

System Dynamics is a discipline for the modeling, simulation and control of complex dynamic systems, founded by Jay W. Forrester [5,6]. A main feature of the SD modeling approach is that the issue modeled is represented by closed feedback loops made up of essentially two kinds of variables – stocks and flows – supplemented by parameters and auxiliary variables. Representation in the form of multiple closed loops, as well as the consideration of delays, enable realistic modeling, which brings the endogenous dynamics generated by the system itself to the fore. Moreover, counterintuitive system behaviors [7] generated in the simulations can lead to important insights for model users.

The methodology of SD is centered around a process which combines modeling and simulation iteratively, thus leading to a continuous improvement of model quality and insights into the domain or issue modeled. Other authors have emphasized the role of modeling as a vehicle for learning, in particular group learning, e.g., Lane [12] and Vennix [17].



Source: Own representation following High Performance Systems, Inc. (1994) and Sterman (2000)

Fig. 1. Ideal-typical scheme of an SD-based theory-building process

We take a new view by conceiving of modeling and simulation as a powerful approach to theory-building. Figure 1 depicts an ideal-typical scheme of that process. Even though this is a general scheme, the process represented therein is essentially a theory-building process with the sequence of formulating a proposition, then testing it, expanding or refining the proposition, and proceeding with further tests, etc.

The starting point is a framing of the issue at hand, including a rough definition of the scope and purpose of the model to be developed. The ensuing collection of empirical data arranged via a first view of reference patterns then supports the clarification of the goals and the formulation of the research questions to be answered. Proceeding from this, a dynamic hypothesis can be formed which explains the unfolding of the reference behavior pattern over time. Besides empirical data, this dynamic hypothesis is also based on theoretical concepts and constructs which result from previous research efforts. The core of the theory-building process thus consists in elaborating a theory by drawing on that dynamic hypothesis as well as testing, corroborating or refuting it. Model quality is successively enhanced and explanation deepened along the path of this iterative process.

In the following, the theory-building along the various stages of this process will be illustrated by instancing the generation of a holistic and consistent theory about the development of individuals' musical tastes, especially their preference for classical music.

3 Application: The Case of Cultural Dynamics

Identifying and framing the issue: For the long-term success of all kinds of enterprises – and hence also orchestras - it is crucial to discover and take opportunities as early as possible as well as to detect and avoid potential threats before they become uncontrollable. Therefore, the anticipative capturing of future realities by interpreting weak signals of external developments is important and might even be critical for the long-term survival of an organization [1].

Various samples of relevant data collected by Hamann [8] suggested that the classical music audience in Germany and Switzerland has a disproportionate number of elderly people when compared to the population as a whole (significance level = 0.001). This is a weak signal. In order to determine whether it indicates a potential threat to German and Swiss orchestras, the causes for the extremely high proportions of elderly people in classical music audiences needed to be understood properly. Unfortunately, the implications of the weak signal for the future size of such audiences and the resulting demand for live performances of classical music remained unclear, since there was no theory about the formation of individuals' affinity with classical music.

Gathering and describing empirical data: Further analyses of time series of relevant data published by the Institut für Demoskopie Allensbach [10] suggest that the proportion of people older than 59 years of age among those who frequently listened to classical music increased between 1994 and 2002 by 47 percent (from 31.8 to 46.8 percent of the total). During the same time-span, the number of classical music listeners relative to the number of pop music listeners decreased by 9 percent. Therefore, the research question to be answered by the study was: “Why is the classical music audience aging faster than the population as a whole, and why is it decreasing in size?”

Formulating a dynamic hypothesis: As one possible explanation for the behavior pattern recognized, the following dynamic hypothesis was formulated: The development of basic musical taste regarding the various general types of music, e.g., classical music, jazz, pop/rock music, folk music, etc., takes place in a socialization phase during adolescence.

After that phase, the basic musical taste of an individual remains more or less the same into later life – apart from a negligibly small number of people changing genre. With pop and rock emerging in the 1950s and 60s, young people have increasingly been socialized under the influence of these new types of music. Consequently, the proportions of classical music listeners have been falling from a high level with each succeeding younger cohort,which is due rather to genuine cohort differences in participation than to any function of demographic and life-stage factors. This means that the classical music audience will dwindle and die out if no appropriate counteractive measures are taken very soon.

Mapping the causal loop structure: In the next stage of the SD-based theory-building process, the results of previous research relevant to the question as to how music preferences develop were reviewed. The existing research results were thoroughly tested for inconsistencies. Since hardly any contradictions could be identified, the isolated theoretical results of previous research were put together like pieces of a puzzle,finally adding up to a holistic and consistent body of theory. We concluded that the extent to which activities with musical relevance are put into practice (repeatedly listening to classical music, playing an instrument, and attending appreciation classes) during the socialization phase in an individual’s adolescence determines his or her fundamental musical orientation with regard to classical music in later life. The reason is that such activities enhance the development of “listening competence”, i.e., what Behne [3] calls the “cognitive components (‘concentrated’ and ‘distancing’)” of listening. This theory on the development of individuals’ basic musical taste was represented by means of a causal loop diagram [8].

Modeling and simulating: An SD model is a mathematically formalized version of a theory. According to Diekmann [4], there are several reasons for modeling quantitatively: First, it conduces to higher precision of the theory, e.g., by specifying the connections between variables as algebraic functions. Secondly, hypotheses can be derived mathematically from formalized theories by which new and surprising insights are often gained. Thirdly, a model allows of testing the theoretical assumptions for inconsistencies in a more stringent fashion and facilitates checking the deduction for errors. Therefore, the theory developed so far was specified as a quantitative model, and many simulations were run. The simulations clearly corroborated the dynamic hypothesis. In addition, deeper insights into the issues under study were gained, which enabled the elaboration of well-founded recommendations for the management of orchestras.

Challenging and validating the model (theoretically and empirically): In theory-building, the quality and robustness of the theoretical propositions developed, i.e., “scientific rigour”, should be the principal concern. We are taking Karl Raimund Popper's [14] logic of scientific discovery – essentially a concept of an evolutionary progress of science – as a benchmark for the design of the theory-building process. This implies that any proposition must be formulated in such a way that it can be disproved if confronted with reality. In other words: it must be proposed in such a way that it can be falsified. The reason for this demand for refutability is that science is advanced by bold propositions or guesses to be subjected to a barrage of criticism. Only hypotheses capable of clashing with facts are regarded as scientifically legitimate.

Thus, every single equation of the model, i.e., propositions regarding causal relationships, had to be carefully examined by drawing on additional theoretical and empirical data. The ability of the model to reproduce the reference behavior pattern is not sufficient. Moreover, as Barlas [2] expresses it, “a system dynamics model must generate the ‘right output behavior for the right reasons’”, i.e., the internal structure of the model has to be valid as well. Hence, the model structure was tested by comparing the model structure with the knowledge about the structure of the real system (direct structure tests) as well as by testing the behavior patterns generated by the model (indirect structure tests). In a concrete example of a structure test, the proportion of women of child-bearing age (i.e., between 15 and 45) was assumed to be approximately constant over time. Empirical data provided by the Federal Statistical Office in Germany revealed that this proportion actually remained within the very narrow range between 48.5 and 48.9 percent during the time-span from 1978 to 2002. Therefore, the so-called parameter-confirmation test (as part of the indirect structure tests) was considered to have been passed.

Finally, the behavior replication tests were not applied before each of the various forms of structure test had been passed. One of the typical tests in this category was a comparison of the time series based on the statistical data about the evolution of the German population in the different age brackets, with the simulated values based on the SD model. The difference between the two is represented in the following formula:

$$D = \int_{t=1980}^{2000} \left| a(t) - s(t) \right| dt \cdot$$

where *a* is the actual development, *s* designates the simulated results and *D* a measure for the divergence between the two. The subsequent aim was to find a value for *s(t)* for which

$$D = D_{\min} = \min_{s} \int_{t=1980}^{2000} \left| a(t) - s(t) \right| dt \cdot$$

The test was regarded as having been passed only when the difference was no longer significant.

Modes of scientific inquiry applied: In the first two stages of SD-based theory-building, the dominant approach is inductive research: First, from particular observations limited to the sample size the age structure of all classical music listeners in Germany and Switzerland respectively, an imbalance was inferred. Secondly, the time series analyzed covered the period from 1994 to 2002. The formulation of the (initial) dynamic hypothesis clearly puts it into the category of abductive research: Eventually, the observed facts were interpreted and explanatory principles obtained by looking beyond the data, which is the very essence of the abductive approach. Finally, integrating the existing theoretical research results into a consistent theory is a deductive process. This is because particular statements regarding the development of an affinity with classical music are concluded from existing theories which are considered to be universally true. In turn, these theories were accepted as universal truths after they had been inferred inductively from particular empirical observations and had withstood a variety of attempts at falsification. This makes it clear that the different modes of scientific inquiry are inextricably bound up together when one is generating theories based on SD methodology.

4 Conclusions

Theory-building is more than an exercise for academics. It is also an indispensable device for practitioners in organizations, allowing them to test their assumptions and bring their speculations down to earth in order to make better decisions. That is why theory-building is a fundamental prerequisite for effective action.

The SD methodology is a powerful and rigorous approach to the development of theories. This is underpinned by its exceptionally high validation standards: Bold guesses, i.e. abductive theory-building, first crystallize in theory, the model then being submitted to numerous tests. Among the methodologies for the modeling of social systems, none, as far as we know, has validation standards as strict as those for SD. For instance, econometrics operates essentially with statistical validation procedures. In SD, the standard procedure for model validation also involves statistical tests, e.g., the comparison of time-series of data representing the object system versus those generated by the simulation. In order to avoid a model's being considered right for the wrong reasons, SD validation includes a whole set of obligatory procedures designed to build up confidence in a model [15]. The abductively acquired elements of the theories therefore do not remain merely speculative, without empirical corroboration.

We have reported an application of SD to the construction of a theory of Cultural Dynamics, from which substantial insights and recommendations for the management of cultural institutions have been derived. Other cases in point have already been published, e.g., Ulli-Beer [16] and Kopainsky [11].

The SD methodology for modeling, simulation and control is in line with the concepts of evolutionary theory-building as proposed by the theory of science. It must be added, however, that it is also highly appropriate for applications, owing to its intuitive techniques and the user-friendly software available.

Summing up, one may say that the potential of SD as a methodology for theory-building is exceedingly high.

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