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ROBERT A. MEYERS, Ph. D.
Editor-in-Chief
RAMTECH LIMITED
122 Escalle Lane
Larkspur, CA 94939
USA
robert.meyers@ramtechlimited.org

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24. Roberts EB (ed) (1978) Managerial applications of system dynamics. MIT Press, Cambridge. Reprinted by Pegasus Communications, Waltham
25. Saeed K (1991) Towards sustainable development: essays on system analysis of national policy. Progressive Publishers, Lahore
26. Senge PM (1990) The fifth discipline: the art and practice of the learning organization. Doubleday/Currency, New York
27. Sterman JD (1988) Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment. *Manag Sci* 35(3):321–339
28. Sterman JD (2001) Business dynamics: systems thinking and modeling for a complex world. Irwin McGraw-Hill, Boston
29. Sterman JD, Sweeney LB (2002) Cloudy skies: assessing public understanding of global warming. *Syst Dyn Rev* 18(2):207–240
30. System Dynamics Review. 1985–present. Wiley, Chichester
31. Vennix JAM (1996) Group model building: facilitating team learning using system dynamics. Wiley, Chichester
32. von Bertalanffy L (1968) General systems theory: foundations, development, applications. George Braziller, New York
33. Warren KD (2002) Competitive strategy dynamics. Wiley, United Kingdom
34. Wolstenholme EF (1990) System enquiry: a system dynamics approach. Wiley, Chichester
35. Wolstenholme EF (2003) Towards the definition and use of a core set of archetypal structures in system dynamics. *Syst Dyn Rev* 19(1):7–26

System Dynamics in the Evolution of the Systems Approach

MARKUS SCHWANINGER

Institute of Management, University of St. Gallen,
St. Gallen, Switzerland

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Glossary

Cybernetics The science of communication and control in complex, dynamical systems. The core objects of study are information, communication, feedback and

adaptation. In the newer versions of cybernetics, the emphasis is on observation, self-organization, self-reference and learning.

Dynamical system The dynamical system concept is a mathematical formalization of time-dependent processes. Examples include the mathematical models that describe the swinging of a clock pendulum, the flow of water in a river, and the evolution of a population of fish in a lake.

Law of requisite variety Ashby's law of requisite variety says: "Only variety can destroy variety". It implies that the varieties of two interacting systems must be in balance, if stability is to be achieved.

Organizational cybernetics The science which applies cybernetic principles to organization. Synonyms are *Management Cybernetics* and *Managerial Cybernetics*.

System There are many definitions of *system*. Two examples: A portion of the world sufficiently well defined to be the subject of study; something characterized by a structure, for example, a social system (Anatol Rapoport). A system is a family of relationships between its members acting as a whole (International Society for the Systems Sciences).

System dynamics A methodology and discipline for the modeling, simulation and control of dynamic systems. The main emphasis falls on the role of structure and its relationship with the dynamic behavior of systems, which are modeled as networks of informationally closed feedback loops between stock and flow variables.

Systems approach A perspective of inquiry, education and management, which is based on system theory and cybernetics.

System theory A formal science of the structure, behavior, and development of systems. In fact there are different system theories. General system theory is a transdisciplinary framework for the description and analysis of any kind of system. System theories have been developed in many domains, e. g., mathematics, computer science, engineering, sociology, psychotherapy, biology and ecology.

Variety A technical term for *complexity* which denotes the number of (potential) states of a system.

Definition of the Subject

The purpose of this chapter is to give an overview of the role of system dynamics (SD) in the context of the evolution of the systems movement. This is necessary because SD is often erroneously taken as the systems approach as such, not as part of it. It is also requisite to show that the

processes of the evolution of both SD in particular and the systems movement as a whole are intimately linked and intertwined. Finally, in view of the purpose of the chapter the actual and potential relationships between system dynamics and the other strands of the systems movement are evaluated. This way, complementarities and synergies are identified.

Introduction

The purpose of this contribution is to give an overview of the role of system dynamics in the context of the evolution of the systems movement. "Systems movement" – often referred to briefly as "systemics" – is a broad term, which takes into account the fact that there is no single system approach, but a range of different ones. The common denominator of the different system approaches in our day is that they share a worldview focused on complex dynamic systems, and an interest in describing, explaining and designing or at least influencing them. Therefore, most of the system approaches offer not only a theory but also a way of thinking ("systems thinking" or "systemic thinking") and a methodology for dealing with systemic issues or problems.

System dynamics (SD) is a discipline and a methodology for the modeling, simulation and control of complex, dynamic systems. SD was developed by MIT professor Jay W. Forrester (e.g. [20,21]) and has been propagated by his students and associates. SD has grown to a school of numerous academics and practitioners all over the world. The particular approach of SD lies in representing the issues or systems-in-focus as meshes of closed feedback loops made up of stocks and flows, in continuous time and subject to delays.

The development of the system dynamics methodology and the worldwide community that applies SD to modeling and simulation in radically different contexts suggest that it is a "systems approach" on its own. Nevertheless, taking "system dynamics" as the (one and only) synonym for "systemic thinking" would be going too far, given the other approaches to systemic thinking as well as a variety of system theories and methodologies, many of which are complementary to SD. In any case, however, the SD community has become the strongest "school" of the Systems approach, if one takes the numbers of members in organizations representing the different schools as a measure (by 2006, the System Dynamics Society had more than 1000 members).

The rationale and structure of this contribution is as follows. Starting with the emergence of the systems approach, the multiple roots and theoretical streams of sys-

temics are outlined. Next, the common grounds and differences among different strands of the systems approach are highlighted, and the various systems methodologies are explored. Then the distinctive features of SD are analyzed. Finally comes a reflection on the relationships of SD with the rest of the systems movement as well as with potential complementarities and synergies.

In Table 1, a time-line overview of some milestones in the evolution of the systems approach in general and System Dynamics in particular is given. Elaborating on each of the sources quoted therein would reach beyond the purpose of this chapter. However, to convey a synoptic view, a diagram showing the different systems approaches and their interrelationships is provided in the Appendix "Systems Approaches – An Overview".

Emergence of the Systems Approach

The systems movement has many roots and facets, with some of its concepts going back as far as ancient Greece. What we name as "the systems approach" today materialized in the first half of the twentieth century. At least two important components should be mentioned: those proposed by von Bertalanffy and by Wiener.

Ludwig von Bertalanffy, an American biologist of Austrian origin, developed the idea that organized wholes of any kind should be describable and, to a certain extent, explainable, by means of the same categories, and ultimately by one and the same formal apparatus. His *general systems theory* triggered a whole movement which has tried to identify invariant structures and mechanisms across different kinds of organized wholes (for example, hierarchy, teleology, purposefulness, differentiation, morphogenesis, stability, ultrastability, emergence, and evolution).

In 1948 Norbert Wiener, an American mathematician at the Massachusetts Institute of Technology, published his seminal book on *Cybernetics*, building upon interdisciplinary work carried out in cooperation with Bigelow, an IBM engineer, and Rosenblueth, a physiologist. Wiener's opus became the transdisciplinary foundation for a new science of capturing as well as designing control and communication mechanisms in all kinds of dynamic systems [81]. Cyberneticists have been interested in concepts such as information, communication, complexity, autonomy, interdependence, cooperation and conflict, self-production ("autopoiesis"), self-organization, (self-) control, self-reference and (self-) transformation of complex dynamic systems.

Along the genetic line of the tradition which led to the evolution of General Systems Theory (von Berta-

lanffy, Boulding, Gerard, Miller, Rapoport) and Cybernetics (Wiener, McCulloch, Ashby, Powers, Pask, Beer), a number of roots can be identified, in particular:

- Mathematics (for example, Newton, Poincaré, Lyapunov, Lotka, Volterra, Rashevsky)
- Logic (for example, Epimenides, Leibniz, Boole, Russell and Whitehead, Goedel, Spencer-Brown)
- Biology, including general physiology and neurophysiology (for example, Hippocrates, Cannon, Rosenblueth, McCulloch, Rosen)
- Engineering and computer science, including the respective physical and mathematical foundations (for example, Heron, Kepler, Watt, Euler, Fourier, Maxwell, Hertz, Turing, Shannon and Weaver, von Neumann, Walsh)
- Social and human sciences, including economics (for example, Hume, Adam Smith, Adam Ferguson, John Stuart Mill, Dewey, Bateson, Merton, Simon, Piaget).

In this last-mentioned strand of the systems movement, one focus of inquiry is on the role of feedback in communication and control in (and between) organizations and society, as well as in technical systems. The other focus of interest is on the multidimensional nature and the multi-level structures of complex systems. Specific theory building, methodological developments and pertinent applications have occurred at the following levels:

- Individual and family levels (for example, systemic psychotherapy, family therapy, holistic medicine, cognitive therapy, reality therapy)
- Organizational and societal levels (for example, managerial cybernetics, organizational cybernetics, socio-cybernetics, social systems design, social ecology, learning organizations)
- The level of complex (socio-)technical systems (systems engineering)

The notion of "socio-technical systems" has become widely used in the context of the design of organized wholes involving interactions of people and technology (for instance, Linstone's multi-perspectives-framework, known by way of the mnemonic TOP (Technical, Organizational, Personal/individual)).

As can be noted from these preliminaries, different kinds of system theory and methodology have evolved over time. One of these is a theory of dynamic systems by Jay W. Forrester, which serves as a basis for the methodology of system dynamics. Two eminent titles are [20] and [21]. In SD, the main emphasis falls on the role of structure and its relationship with the dynamic behavior of systems, modeled as networks of informationally closed

feedback loops between stock and flow variables. Several other mathematical systems theories have been elaborated, for example, mathematical general systems theory (Klir, Pestel, Mesarovic and Takahara), as well as a whole stream of theoretical developments which can be subsumed under the terms "dynamic systems theory" or "theories of non-linear dynamics" (for example, catastrophe theory, chaos theory and complexity theory). Under the latter, branches such as the theory of fractals (Mandelbrot), geometry of behavior (Abraham), self-organized criticality (Bak), and network theory (Barabasi, Watts) are subsumed. In this context, the term "sciences of complexity" is used.

In addition, a number of mathematical theories, which can be called "system theories," have emerged in different application contexts, examples of which are discernible in the following fields:

- Engineering, namely information and communication theory (Shannon and Weaver), technology and computer-aided systems theory (for example, control theory, automata, cellular automata, agent-based modeling, artificial intelligence, cybernetic machines, neural nets)
- Operations research (for example, modeling theory and simulation methodologies, Markov chains, genetic algorithms, fuzzy control, orthogonal sets, rough sets)
- Social sciences, economics in particular (for example, game theory, decision theory)
- Biology (for example, Sabelli's Bios theory of creation)
- Ecology (for example, E. and H. Odum's systems ecology).

Most of these theories are transdisciplinary in nature, i. e., they can be applied across disciplines. The Bios theory, for example is applicable to clinical, social, ecological and personal settings [54]. Examples of essentially non-mathematical system theories can be found in many different areas of study, e. g.:

- Economics, namely its institutional/evolutionist strand (Veblen, Myrdal, Boulding, Dopfer)
- Sociology (for example, Parsons' and Luhmann's social system theories, Hall's cultural systems theory)
- Political sciences (for example, Easton, Deutsch, Wallerstein)
- Anthropology (for example, Levi Strauss's structuralist-functionalist anthropology, Margaret Mead)
- Semiotics (for example, general semantics (Korzybski, Hayakawa, Rapoport), cybersemiotics (Brier))
- Psychology and psychotherapy (for example, systemic intervention (Bateson, Watzlawick, F. Simon), and fractal affect logic (Ciompi))

- Ethics and epistemology (for example, Vickers, Churchman, von Foerster, van Gigch)

Several system-theoretic contributions have merged the quantitative and the qualitative in new ways. This is the case for example in Rapoport's works in game theory as well as general systems theory, Pask's conversation theory, von Foerster's cybernetics of cybernetics (second-order cybernetics), and Stafford Beer's opus in managerial cybernetics. In all four cases, mathematical expression is virtuously connected to ethical, philosophical, and epistemological reflection. Further examples are Prigogine's theory of dissipative structures, Mandelbrot's theory of fractals, complex adaptive systems (Holland et al.), Kauffman's complexity theory, and Haken's synergetics, all of which combine mathematical analysis and a strong component of qualitative interpretation.

A large number of systems methodologies, with the pertinent threads of systems practice, have emanated from these theoretical developments. Many of them are expounded in detail in specialized encyclopedias (e.g., [27] and, under a specific theme, named *Systems Science and Cybernetics*, of the Encyclopedia of Life Support Systems [18]). In this chapter, only some of these will be addressed explicitly, in order to shed light on the role of SD as part of the systems movement.

Common Grounds and Differences

Even though the spectrum of system theories and methodologies outlined in the preceding section may seem multifarious, all of them have a strong common denominator: They build on the idea of systems as organized wholes. An objectivist working definition of a system is that of a whole, the organization of which is made up by interrelationships. A subjectivist definition is that of a set of interdependent variables in the mind of an observer, or, a mental construct of a whole, an aspect that has been emphasized by the position of constructivism. *Constructivism* is a synonym for *second-order cybernetics*. While first-order cybernetics concentrates on regulation, information and feedback, second-order cybernetics focuses on observation, self-organization and self-reference. Heinz von Foerster established the distinction between 'observed systems' for the former and 'observing systems' for the latter [74].

From the standpoint of operational philosophy, a system is, as Rapoport says, "a part of the world, which is sufficiently well defined to be the object of an inquiry or also something, which is characterized by a structure, for example, a production system" [50].

In recent systems theory, the aspect of relationships has been emphasized as the main building block of a sys-

tem, as one can see from a definition published by the International Society for the Systems Sciences (ISSS): "A system is a family of relationships between its members acting as a whole" [63]. Also, purpose and interaction have played an important part in reflections on systems: Systems are conceived, in the words of Forrester [21], as "wholes of elements, which cooperate towards a common goal." Purposeful behavior is driven by internal goals, while purposive behavior rests on a function assigned from the outside. Finally, the aspects of open and closed functioning have been emphasized. Open systems are characterized by the import and export of matter, energy and information. A variant of particular relevance in the case of social systems is the operationally closed system, that is, a system which is self-referential in the sense that its self-production (autopoiesis) is a function of production rules and processes by which order and identity are maintained, and which cannot be modified directly from outside. As we shall see, this concept of operational closure is very much in line with the concept of circularity used in SD.

At this point, it is worth elaborating on the specific differences between two major threads of the systems movement, which are of special interest because they are grounded in "feedback thought" [52]: The cybernetic thread, from which organizational cybernetics has emanated, and the servomechanic thread in which SD is grounded. As Richardson's detailed study shows, the strongest influence on cybernetics came from biologists and physiologists, while the thinking of economists and engineers essentially shaped the servomechanic thread. Consequently, the concepts of the former are more focused on the adaptation and control of complex systems for the purpose of maintaining stability under exogenous disturbances. Servomechanics, on the other hand, and SD in particular, take an endogenous view, being mainly interested in understanding circular causality as the principal source of a system's behavior. Cybernetics is more connected with communication theory, the general concern of which can be summarized as how to deal with randomly varying input. SD, on the other hand, shows a stronger link with engineering control theory, which is primarily concerned with behavior generated by the control system itself, and by the role of nonlinearities. Managerial cybernetics and SD both share the concern of contributing to management science, but with different emphases and with instruments that are different but in principle complementary. Finally, the mathematical foundations are generally more evident in the basic literature on SD than in the writings on organizational cybernetics, in which the formal apparatus underlying model formulation is confined to a small number of publications (e.g., [7,10]),

which are less known than the qualitative treatises. The terms *management cybernetics* and *managerial cybernetics* are used as synonyms for *organizational cybernetics*.

The Variety of Systems Methodologies

The methodologies that have evolved as part of the systems movement cannot be expounded in detail here. The two epistemological strands in which they are grounded, however, can be identified – the positivist tradition and the interpretivist tradition.

Positivist tradition denotes those methodological approaches that focus on the generation of “positive knowledge,” that is, a knowledge based on “positively” ascertained facts. *Interpretivist tradition* denotes those methodological approaches that emphasize the importance of subjective interpretations of phenomena. This stream goes back to Greek art and science of the interpretation and understanding of texts.

Some systems methodologies have been rooted in the positivist tradition, and others in the interpretivist tradition. The differences between the two can be described along the following set of polarities:

- An objectivist versus a subjectivist position
- A conceptual-instrumental versus a communicational/cultural/political rationality
- An inclination to quantitative versus qualitative modeling
- A structuralist versus a discursive orientation.

A positivistic methodological position tends toward the objectivistic, conceptual-instrumental, quantitative and structuralist-functionalist in its approach. An interpretive position, on the other hand, tends to emphasize the subjectivist, communicational, cultural, political, ethical and esthetic—that is, the qualitative and discursive aspects. It would be too simplistic to classify a specific methodology in itself as being “positivistic” or “interpretative”. Despite the traditions they have grown out of, several methodologies have evolved and been reinterpreted or opened to new aspects (see below).

In the following, a sample of systems methodologies will be characterized and positioned in relation to these two traditions, beginning with those in the positivistic strand:

- *“Hard” OR methods.* Operations research (OR) uses a wide variety of mathematical and statistical methods and techniques—for example of optimization, queuing, dynamic programming, graph theory, time series analysis—to provide solutions for organizational and man-

agerial problems, mainly in the operational domains of production and logistics, and in finance.

- *Living systems theory.* In his LST, James Grier Miller [44] identifies a set of 20 necessary components that can be discerned in living systems of any kind. These structural features are specified on the basis of a huge empirical study and proposed as the “critical subsystems” that “make up a living system.” LST has been used as a device for diagnosis and design in the domains of engineering and the social sciences.
- *Viable system model.* To date, Stafford Beer’s VSM is probably the most important product of organizational cybernetics. It specifies a set of management functions and their interrelationships as the sufficient conditions for the viability of any human or social system (see [10]). These are applicable in a recursive mode, for example, to the different levels of an organization. The VSM has been widely applied in the diagnostic mode, but also to support the design of all kinds of social systems. Specific methodologies for these purposes have been developed, for instance for use in consultancy. The term viable system diagnosis (VSD) is also used.

The methodologies and models addressed up to this point have by and large been created in the positivistic tradition of science. Other strands in this tradition do exist, e.g., systems analysis and systems engineering, which together with OR have been called “hard systems thinking” (p. 127 in [31]). Also, more recent developments such as mathematical complexity and network theories, agent-based modeling and most versions of game theory can be classified as hard systems approaches.

The respective approaches have not altogether been excluded from fertile contacts with the interpretivist strand of inquiry. In principle, all of them can be considered as instruments for supporting discourses about different interpretations of an organizational reality or alternative futures studied in concrete cases. In our time, most applications of the VSM, for example, are constructivist in nature. To put it in a nutshell, these applications are (usually collective) constructions of a (new) reality, in which observation and interpretation play a crucial part. In this process, the actors involved make sense of the system under study, i.e., the organization in focus, by mapping it on the VSM. At the same time they bring forth “multiple realities rather than striving for a fit with one reality” (p. 299 in [29]).

The second group of methodologies is part of the interpretive strand:

- *Interactive Planning.* IP is a methodology, designed by Russell Ackoff [1], and developed further by Jamshid

Gharajedaghi [28], for the purpose of dealing with “messes” and enabling actors to design their desired futures, as well as to bring them about. It is grounded in theoretical work on purposeful systems, reverts to the principles of continuous, participative and holistic planning, and centers on the idea of an “idealized design.”

- *Soft Systems Methodology*. SSM is a heuristic designed by Peter Checkland [13,14] for dealing with complex situations. Checkland suggests a process of inquiry constituted by two aspects: A conceptual one, which is logic based, and a sociopolitical one, which is concerned with the cultural feasibility, desirability and implementation of change.
- *Critical Systems Heuristics*. CSH is a methodology, which Werner Ulrich [67,68] proposed for the purpose of scientifically informing planning and design in order to lead to an improvement in the human condition. The process aims at uncovering the interests that the system under study serves. The legitimacy and expertise of actors, and particularly the impacts of decisions and behaviors of the system on others – the “affected” – are elicited by means of a set of boundary questions. CSH can be seen as part of a wider movement known as the “Emancipatory Systems Approach” which embraces, e. g., Freire’s Critical Pedagogy, Interpretive Systemology, and Community OR (see pp. 291ff in [31]).

All three of these methodologies (IP, SSM, and CSH) are positioned in the interpretive tradition. Other methodologies and concepts which can be subsumed under the interpretive systems approach are, e. g., Warfield’s science of generic design, Churchman’s social system design, Senge’s soft systems thinking, Mason and Mitroff’s strategic assumptions surfacing and testing (SAST), Eden and Ackermann’s strategic options in development and analysis (SODA), and other methodologies of soft operational research (for details, see pp. 211ff in [31]). The interpretive methodologies were designed to deal with qualitative aspects in the analysis and design of complex systems, emphasizing the communicational, social, political and ethical dimensions of problem solving. Several authors mention explicitly that they do not preclude the use of quantitative techniques or include such techniques in their repertoire (e. g., the biocyberneticist Frederic Vester).

In an advanced understanding of system dynamics both of these traditions—positivist and interpretivist—are synthesized. The adherents of SD conceive of model building and validation as a semi-formal, relativistic, holistic social process. Validity is understood as usefulness or fit-

ness in relation to the purpose of the model, and validation as an elaborate set of procedures – including logico-structural, heuristic, algorithmic, statistical, and also discursive components – by which the quality of and the confidence in a model are gradually improved (see [4,5,59]).

System Dynamics – Its Features, Strengths and Limitations

The features, strengths and limitations of the SD methodology are a consequence of its specific characteristics. In the context of the multiple theories and methodologies of the systems movement, some of the distinctive features of SD are (for an overview, see [52], pp. 142ff in [31]):

- *Feedback as conceptual basis*. SD model systems are high-order, multiple-loop networks of closed loops of information. Concomitantly, an interest in non-linearities, long-term patterns and internal structure rather than external disturbances is characteristic of SD (p. 31 in [40]). However, SD models are not “closed systems”, as sometimes is claimed, in the sense that (a) flows can originate from outside the system’s boundaries, (b) representations of exogenous factors or systems can be incorporated into any model as parameters or special modules, and (c) new information can be accommodated via changes to a model. In other words, the SD view hinges on a view of systems which are closed in a causal sense but not materially (p. 297 in [52]).
- *Focus on internally generated dynamics*. SD models are conceived as closed systems. The interest of users is in the dynamics generated inside those systems. Given the nature of closed feedback loops and the fact that delays occur within them, the dynamic behavior of these systems is essentially non-linear.
- *Emphasis on understanding*. For system dynamicists the understanding of the dynamics of a system is the first goal to be achieved by means of modeling and simulation. Conceptually, they try to understand events as embedded in patterns of behavior, which in turn are generated by underlying structures. Such understanding is enabled by SD as it “shows how present policies lead to future consequences” (Sect. VIII in [23]). Thereby, the feedback loops are “a major source of puzzling behavior and policy difficulties” (p. 300 in [52]). SD models purport to test mental models, hone intuition and improve learning (see [65]).
- *High degree of operationality*. SD relies on formal modeling. This fosters disciplined thinking; assumptions, underlying equations and quantifications must be clarified. Feedback loops and delays are visualized and formalized; therewith the causal logic inherent in a model

is made more transparent and discussable than in most other methodologies [53]. Also, a high level of realism in the models can be achieved. SD is therefore apt to support decision-making processes effectively.

- *Far-reaching requirements (and possibilities) for the combination of qualitative and quantitative aspects of modeling and simulation.* This is a consequence of the emphasis on understanding. The focus is not on point-precise prediction, but on the generation of insights into the patterns generated by the systems under study.
- *High level of generality and scale robustness.* The representation of dynamic systems in terms of stocks and flows is a generic form, which is adequate for a wide spectrum of potential applications. This spectrum is both broad as to the potential subjects under study, and deep as to the possible degrees of resolution and detail [38]. In addition, the SD methodology enables one to deal with large numbers of variables within multiple interacting feedback loops (p. 9 in [22]). SD has been applied to the most diverse subject areas, e.g., global modeling, environmental issues, social and economic policy, corporate and public management, regional planning, medicine, psychology and education in mathematics, physics and biology.

The features of SD just sketched out result in both strengths and limitations. We start with the strengths.

Strengths of SD

1. Its *specific modeling approach* makes SD particularly helpful in gaining insights into the patterns exhibited by dynamic systems, as well as the structures underlying them. Closed-loop modeling has been found most useful in fostering understanding of the dynamic functioning of complex systems. Such understanding is especially facilitated by the principle of modeling the systems or issues under study in a continuous mode and at rather high aggregation levels [20,38]. With the help of relatively small but insightful models, and by means of sensitivity analyses as well as optimization heuristics incorporated in the application software packages, decision-spaces can be thoroughly explored. Vulnerabilities and the consequences of different system designs can be examined with relative ease.
2. The *generality of the methodology* and its power to crystallize operational thinking in realistic models have triggered applications in the most varied contexts. Easy-to-use software and the features of screen-driven modeling via graphic user interfaces provide a strong lever for collaborative model-building in teams (cf. [2,69]).

3. Another strong point is the *momentum of the SD movement*. Due to the strengths commented above this point, the community of users has grown steadily, being probably the largest community within the systems movement. Lane (p. 484 in [36]) has termed SD "one of the most widely used systems approaches in the world."
4. Its specific features make SD an exceptionally effective tool for *conveying systemic thinking* to anybody. Therefore, it also has an outstanding track-record of classroom applications for which "learner-directed learning" [24] or "learner-centered learning" is advocated [25,26]. Pertinent audiences range from schoolchildren at the levels of secondary and primary schools to managers and scientists.

Given these strengths, the community of users has not only grown significantly, but has also transcended disciplinary boundaries, ranging from the formal and natural sciences to the humanities, and covering multiple uses from theory building and education to the tackling of real-world problems at almost any conceivable level. Applications to organizational, societal and ecological issues have seen a particularly strong growth. This feeds back on the availability and growth of the knowledge upon which the individual modeler can draw.

The flip side of most of the strengths outlined here embodies the limitations of SD; we concentrate on those which can be relevant to a possible complementarity of SD with other systems methodologies.

Limitations of SD

1. The main point here is that SD does not provide a framework or methodology for the *diagnosis and design* of organizational structures in the sense of inter-relationships among organizational actors. This makes SD susceptible to completion from without – a completion which organizational cybernetics (OC), and the VSM in particular, but also living system theory (LST), especially can provide. The choice falls on these two approaches because of their strong heuristic power and their complementary strengths in relation to SD (cf. [57,61]).
2. Another limitation of SD is related to the *absorption of variety* (complexity) by an organization. *Variety* is a technical term for *complexity*, which denotes a (high) number of potential states or behaviors of a system (based on [3,8]). SD offers an approach to the handling of variety which allows modeling at different scales of a problem or system [47]. It focuses on the identification, at a certain resolution level or possibly several resolution levels, of the main stock variables which will be

affected by the respective flows. These, in turn, will be influenced by parameters and auxiliary variables. This approach, even though it enables thinking and modeling at different scales, does not provide a formal procedure for an organization to cope with the external complexity it faces, namely, for designing a structure which can absorb that complexity. In contrast, OC and LST offer elaborate models to enable the absorption of variety, in the case of the VSM based explicitly on Ashby's *Law of Requisite Variety*. It says "Only variety can destroy variety", which implies that the varieties of two interacting systems must be in balance, if stability is to be achieved [3]. The VSM has two salient features in this respect. Firstly, it helps design an organizational unit for viability, by enabling it to attenuate the complexity of its environment, and also to enhance its eigenvariety, so that the two are in balance. The term *variety engineering* has been used in this context [9]. Secondly, the recursive structure of the VSM ensures that an organization with several levels will develop sufficient eigenvariety along the fronts on which the complexity it faces unfolds. Similarly, LST offers the conditions for social systems to survive, by maintaining thermodynamically highly improbable energy states via continuous interaction with their environments. The difference between the two approaches is that the VSM functions more in the strategic and informational domains, while the LST model essentially focuses on the operational domain. In sum, both can make a strong contribution related to coping with the external complexity faced by organizations, and therefore can deliver a strong complement to SD.

3. Finally, the design of *modeling processes* confronts SD with specific challenges. The original SD methodology of modeling and simulation was to a large extent functionally and technically oriented. This made it strong in the domain of logical analysis, while the socio-cultural and political dimensions of the modeling process were, if not completely out of consideration, at least not a significant concern in methodological developments. The SD community – also under the influence of the soft systems approaches – has become aware of this limitation and has worked on incorporating features of the social sciences into its repertoire. The following examples, which document this effort to close the gap, stand for many. Extensive work on group model building has been achieved, which explores the potential of collaborative model building [69]. A new schema for the modeling process has been proposed, which complements logic-based analysis by cultural analysis [37]. The social dimension of system dynamics-based modeling has be-

come subject to intensive discussion ([77]; and other contributions to the special issue of *Systems Research and Behavioral Science*, Vol. 51, No. 4, 2006). Finally, in relation to consultancy methodology, modeling has been framed as a learning process [34] and as second-order intervention [60].

As has been shown, there is a need to complement classical SD with other methodologies, when issues are at stake which it cannot handle by itself. VSM and LST are excellent choices when issues of organizational diagnosis or design are to be tackled.

The limitations addressed here call attention to other methodologies which exhibit certain features that traditionally were not incorporated, or at least not explicit, in SD methodology. One aspect concerns the features that explicitly address the subjectivity of purposes and meanings ascribed to systems. In this context, support for problem formulation, model construction and strategy design by individuals on the one hand and groups on the other are relevant issues. Also, techniques for an enhancement of creativity (e. g., the generation and the reframing of options) in both individuals and groups are a matter of concern. Two further aspects relate to methodological arrangements for coping with the specific issues of negotiation and alignment in pluralist and coercive settings.

As far as the modeling processes are concerned, group model building has proven to be a valuable complement to pure modeling and simulation. However, there are other systems methodologies which should be considered as potentially apt to enrich SD analysis, namely the soft approaches commented upon earlier, e. g., interactive planning, soft system methodology and critical system heuristics.

On the other hand, SD can be a powerful complement to other methodologies which are more abstract or more static in nature. This potential refers essentially to all systems approaches which stand in the interpretive ("soft") tradition, but also to approaches which stand in the positivist traditions, such as the VSM and LST. These should revert to the support of SD in the event that tradeoffs between different goals must be handled, or if implications of long-term decisions on short-term outcomes (and vice versa) have to be ascertained, and whenever contingencies or vulnerabilities must be assessed.

Actual and Potential Relationships

It should be clear by now that the systems movement has bred a number of theories and methodologies, none of which can be considered all-embracing or complete. All of

them have their strengths and weaknesses, and their specific potentials and limitations.

Since Burrell and Morgan [12] adverted to incommensurability between different paradigms of social theory, several authors have acknowledged or even advocated methodological complementarity. They argue that there is a potential complementarity between different methods, and, one may add, models, even if they come from distinct paradigms. Among these authors are, e.g., Brocklesby [11], Jackson [30], Midgley [43], Mingers [45], Schwaninger [55] and Yolles [83]. These authors have opened up a new perspective in comparison with the non-complementaristic state-of-the-art.

In the past, the different methodologies have led to the formation of their own traditions and "schools," with boundaries across which not much dialogue has evolved. The methodologies have kept their protagonists busy testing them and developing them further. Also, the differences between different language games and epistemological traditions have often suggested incommensurability, and therewith have impaired communication. Prejudices and a lack of knowledge of the respective other side have accentuated this problem: Typically, "hard" systems scientists are suspicious of "soft" systems scientists. For example, many members of the OR community, not unlike orthodox quantitatively oriented economists, adhere to the opinion that "SD is too soft." On the other hand the protagonists of "soft" systems approaches, even though many of them have adopted feedback diagrams (causal loop diagrams) for the sake of visualization, are all too often convinced that "SD is too hard." Both of these judgments indicate a lack of knowledge, in particular of the SD validation and testing methods available, on the one hand, and the technical advancements achieved in modeling and simulation, on the other (see [5,59,66]).

In principle, both approaches are complementary. The qualitative view can enrich quantitative models, and it is connected to their philosophical, ethical and esthetical foundations. However, qualitative reasoning tends to be misleading if applied to causal network structures without being complemented by formalization and quantification of relationships and variables. Furthermore, the quantitative simulation fosters insights into qualitative patterns and principles. It is thus a most valuable device for validating and honing the intuition of decision makers, via corroboration and falsification.

Proposals that advocate mutual learning between the different "schools" have been formulated inside the SD community (e.g., [35]). The International System Dynamics Conference of 1994 in Stirling, held under the banner of "Transcending the Boundaries," was dedicated to the dia-

logue between different streams of the systems movement.

Also, from the 1990s onwards, there were vigorous efforts to deal with methodological challenges, which traditionally had not been an important matter of scientific interest within the SD community. Some of the progress made in these areas is documented in a special edition of *Systems Research and Behavioral Science* (Vol. 21 No. 4, July-August 2004). The main point is that much of the available potential is based on the complementarity, not the mutual exclusiveness, of the different system approaches.

In the future, much can be gained from leveraging these complementarities. Here are two examples of methodological developments in this direction, which appear to be achievable and potentially fertile: The enhancement of qualitative components in "soft" systems methodologies in the process of knowledge elicitation and model building (cf. [69]), and the combination of cybernetics-based organizational design with SD-based modeling and simulation (cf. [61]). Potential complementarities exist not only across the qualities – quantities boundary, but also within each one of the domains. For example, with the help of advanced software, SD modeling ("top-down") and agent-based modeling ("bottom-up") can be used in combination.

From a meta-methodological stance, generalist frameworks have been elaborated which contain blueprints for combining different methodologies where this is indicated. Two examples are:

- *Total systems intervention* (TSI) is a framework proposed by Flood and Jackson [19], which furnishes a number of heuristic schemes and principles for the purpose of selecting and combining systems methods/methodologies in a customized way, according to the issue to be tackled. SD is among the recommended "tools".
- *Integrative systems methodology* (ISM) is a heuristic for providing actors in organizations with requisite variety, developed by Schwaninger [55,56]. It advocates (a) dealing with both content- and context-related issues during the process, and (b) placing a stronger emphasis on the validation of qualitative and quantitative models as well as strategies, in both dimensions of the content of the issue under study and the organizational context into which that issue is embedded. For this purpose, the tools of SD (to model content) and organizational cybernetics – the VSM (to model context) – are cogently integrated.

These are only two examples. In principle, SD could make an important contribution in the context of most of

the methodological frameworks, far beyond the extent to which this has been the case. Systems methodologists and practitioners can potentially benefit enormously from including SD methodology in their repertoires.

Outlook

There have recently been calls for an eclectic "mixing and matching" of methodologies. In light of the epistemological tendencies of our time towards radical relativism, it is necessary to warn against taking a course in which "anything goes". It is most important to emphasize that the desirable methodological progress can only be achieved on the grounds of scientific rigor. This postulate of "rigor" is not to be confused with an encouragement of "rigidity." The necessary methodological principles advocated here are disciplined thinking, a permanent quest for better models (that is, thorough validation), and the highest achievable levels of transparency in the formalizations as well as of the underlying assumptions and sources used. Scientific rigor, in this context, also implies that combinations of methodologies reach beyond merely eclectic additions from different methodologies, so that genuine integration towards better adequacy to the issues at hand is achieved.

The contribution of system dynamics can come in the realms of the following:

- Fostering disciplined thinking
- Understanding dynamic behaviors of systems and the structures that generate them
- Exploring paths into the future and the concrete implications of decisions
- Assessing strategies as to their robustness and vulnerabilities, in ways precluded by other, more philosophical, and generally "soft" systems approaches

These latter streams can contribute to reflecting and tackling the meaning- and value-laden dimensions of complex human, social and ecological systems. Some of their features should and can be combined synergistically with system dynamics, particularly by being incorporated into the repertoires of system dynamicists. From the reverse perspective, incorporating system dynamics as a standard tool will be of great benefit for the broad methodological frameworks. Model formalization and dynamic simulation may even be considered necessary components for the study of the concrete dynamics of complex systems.

Finally, there are also many developments in the "hard", i.e., mathematics-, statistics-, logic-, and informatics-based methods and technologies, which are apt to enrich the system dynamics methodology, namely in

terms of modeling and decision support. For example, the constantly evolving techniques of time-series analysis, filtering, neural networks and control theory can improve the design of system-dynamics-based systems of (self-)control. Also, a bridge across the divide between the top-down modeling approach of SD and the bottom-up approach of agent-based modeling appears to be feasible. Furthermore, a promising perspective for the design of genuinely "intelligent organizations" emerges if one combines SD with advanced database-management, cooperative model building software, and the qualitative features of the "soft" systems methodologies.

The approaches of integrating complementary methodologies outlined in this contribution definitely mark a new phase in the history of the systems movement.

Appendix

Milestones in the Evolution of the Systems Approach in General and System Dynamics in Particular

The table gives an overview of the systems movement's evolution, as shown in its main literature; and that overview is not exhaustive.

Systems Approaches – An Overview

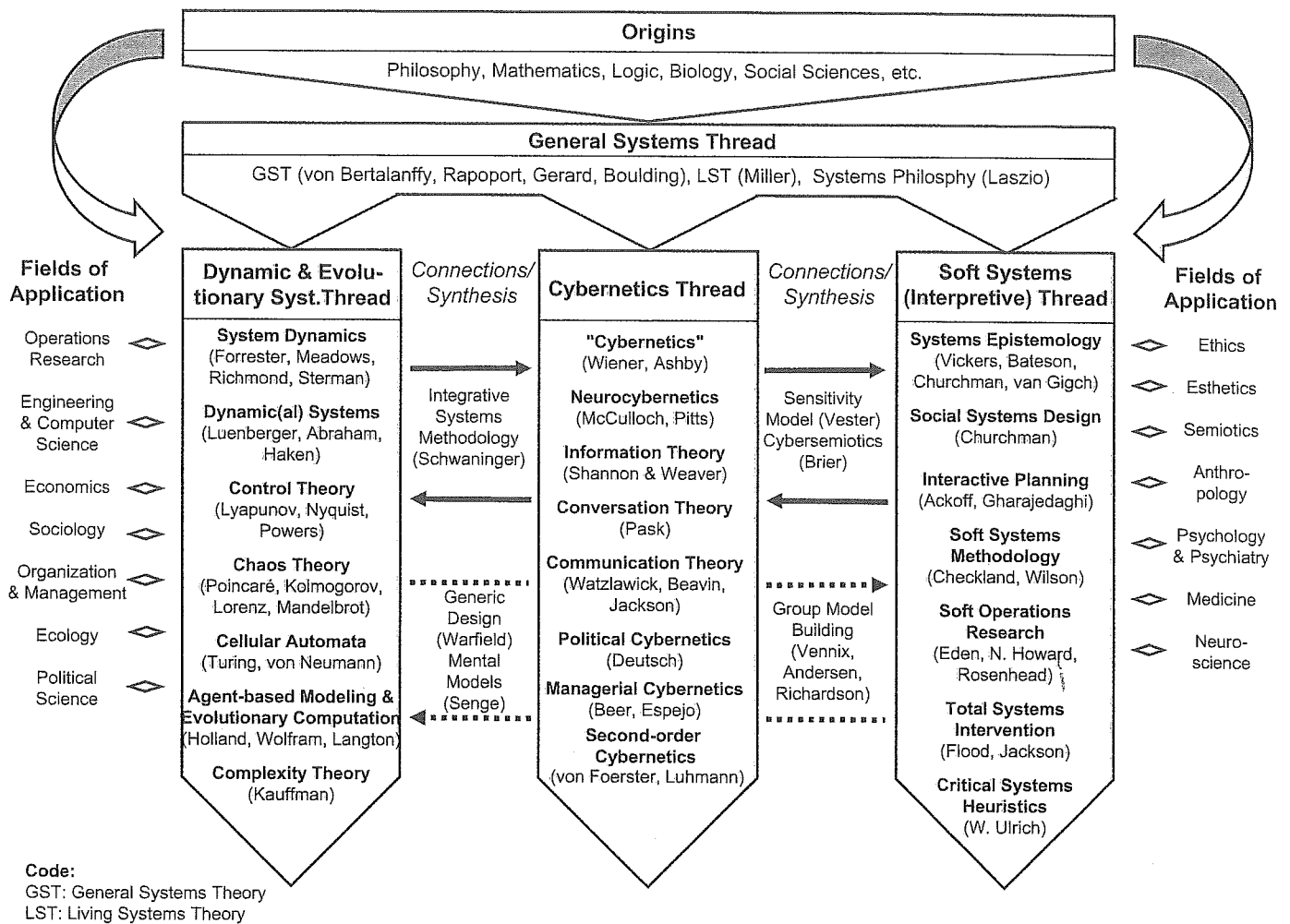
Note: This diagram shows three streams of the systems approach in the context of their antecedents. The general systems thread has its origins in philosophical roots from antiquity: The term *system* derives from the old Greek *σύστημα* (*syntēma*), while, *cybernetics* stems from the Greek *κυβερνήτης* (*kybernētēs*). The arrows between the threads stand for interrelationships and efforts to synthesize the connected approaches. For example, integrated systems methodology is an integrative attempt to leverage the complementarities of system dynamics and organizational cybernetics. Enumerated to the left and right of the scheme are the fields of application. The big arrows in the upper region of the diagram indicate that the roots of the systems approach continue influencing the different threads and the fields of application even if the path via general systems theory is not pursued.

The diagram is not a complete representation, but the result of an attempt to map the major threads of the systems movement and some of their interrelations. Hence, the schema does not cover all schools or protagonists of the movement. Why does the diagram show a dynamic and evolutionary systems thread and a cybernetics thread, if cybernetics is about dynamic systems? The latter embraces all the approaches that are explicitly grounded in cybernetics. The former relates to all other approaches

System Dynamics in the Evolution of the Systems Approach, Table 1

Milestones in the evolution of the systems approach in general and system dynamics in particular

Foundations of general system theory		
Von Bertalanffy	Zu einer allgemeinen Systemlehre	1945
	An Outline of General System Theory	1950
	General System Theory	1968
Bertalanffy, Boulding, Gerard, Rapoport	Foundation of the Society for General Systems Research	1953
Klir	An Approach to General System Theory	1968
Simon	The Sciences of the Artificial	1969
Pichler	Mathematische Systemtheorie	1975
Miller	Living Systems	1978
Mesarovic & Takahara	Abstract Systems Theory	1985
Rapoport	General System Theory	1986
Foundations of cybernetics		
Macy Conferences (Josiah Macy, Jr. Foundation)	Cybernetics. Circular Causal, and Feedback Mechanisms in Biological and Social Systems	1946–1951
Wiener	Cybernetics or Control and Communication in the Animal and in the Machine	1948
Ashby	An Introduction to Cybernetics	1956
Pask	An Approach to Cybernetics	1961
Von Foerster, Zopf	Principles of Self-Organization	1962
McCulloch	Embodiments of Mind	1965
Foundations of organizational cybernetics		
Beer	Cybernetics and Management	1959
	Towards the Cybernetic Factory	1962
	Decision and Control	1966
	Brain of the Firm	1972
Von Foerster	Cybernetics of Cybernetics	1974
Foundations of system dynamics		
Forrester	Industrial Dynamics	1961
	Principles of Systems	1968
	Urban Dynamics	1969
	World Dynamics	1971
Meadows et al.	Limits to Growth	1972
Richardson	Feedback Thought in Social Science and Systems Theory	1991
Systems methodology		
Churchman	Challenge to Reason	1968
	The Systems Approach	1968
Vester & von Hesler	Sensitivitätsmodell	1980
Checkland	Systems Thinking, Systems Practice	1981
Ackoff	Creating the Corporate Future	1981
Ulrich	Critical Heuristics of Social Planning	1983
Warfield	A Science of Generic Design	1994
Schwaninger	Integrative Systems Methodology	1997
Gharajedaghi	Systems Thinking	1999
Sabelli	Bios – A Study of Creation	2005
Selected recent works in system dynamics		
Senge	The Fifth Discipline	1990
Barlas & Carpenter	Model Validity	1990
Vennix	Group Model Building	1996
Lane & Oliva	Synthesis of System Dynamics and Soft Systems Methodology	1998
Sterman	Business Dynamics	2000
Warren	Strategy Dynamics	2002, 2008
Wolstenholme	Archetypal Structures	2003
Morecroft	Strategic Modelling	2007
Schwaninger & Grösser	Theory-building with System Dynamics & Model Validation	2008, 2009



System Dynamics in the Evolution of the Systems Approach, Figure 1

concerned with dynamic or evolutionary systems. The simplification made it necessary to somewhat curtail logical perfection for the sake of conveying a synoptic view of the different systems approaches, in a language that uses the categories common in current scientific and professional discourse. Overlaps exist, e. g., between dynamic systems and chaos theory, cellular automata and agent-based modeling.

Bibliography

Primary Literature

- Ackoff RL (1981) Creating the Corporate Future. Wiley, New York
- Andersen DF, Richardson GP (1997) Scripts for Group Model Building. Syst Dyn Rev 13(2):107-129
- Ashby WR (1956) An Introduction to Cybernetics. Chapman & Hall, London
- Barlas Y (1996) Formal aspects of model validity and validation in system dynamics. Syst Dyn Rev 12(3):183-210
- Barlas Y, Carpenter S (1990) Philosophical roots of model validity: Two paradigms. Syst Dyn Rev 6(2):148-166
- Beer S (1959) Cybernetics and Management. English Universities Press, London
- Beer S (1994) Towards the Cybernetic Factory. In: Harnden R, Leonard A (eds) How Many Grapes Went into the Wine. Stafford Beer on the Art and Science of Holistic Management. Wiley, Chichester, pp 163-225 (reprint, originally published in 1962)
- Beer S (1966) Decision and Control. Wiley, Chichester
- Beer S (1979) The Heart of Enterprise. Wiley, Chichester
- Beer S (1981) Brain of the Firm, 2nd edn. Wiley, Chichester
- Brocklesby J (1993) Methodological complementarity or separate paradigm development – Examining the options for enhanced operational research. Aust J Manag 18(2):133-157
- Burrell G, Morgan G (1979) Sociological Paradigms and Organisational Analysis. Hants, Gower
- Checkland PB (1981) Systems Thinking, Systems Practice. Wiley, Chichester
- Checkland PB, Poulter J (2006) Learning for Action: A Short Definitive Account of Soft Systems Methodology, and its Use Practitioners, Teachers and Students. Wiley, Chichester
- Churchman CW (1968) Challenge to Reason. McGraw-Hill, New York
- Churchman CW (1968) The Systems Approach. Delacorte Press, New York
- Churchman CW (1979) The Systems Approach and its Enemies. Basic Books, New York
- Encyclopedia of Life Support Systems (2002) published under: <http://www.eolss.net/>

19. Flood RL, Jackson MC (1991) *Creative Problem Solving*. Total Systems Intervention. Wiley, Chichester
20. Forrester JW (1961) *Industrial Dynamics*. MIT Press, Cambridge
21. Forrester JW (1968) *Principles of Systems*. MIT Press, Cambridge
22. Forrester JW (1969) *Urban Dynamics*. MIT Press, Cambridge
23. Forrester JW (1971) *World Dynamics*. Pegasus Communications, Waltham
24. Forrester JW (1993) System Dynamics and the Lessons of 35 Years. In: DeGreene KB (ed) *Systems-Based Approach to Policy Making*. Kluwer, Boston
25. Forrester JW (1993) System Dynamics as an Organizing Framework for Pre-college Education. *Syst Dyn Rev* 9(2):183–194
26. Forrester JW (1997) System Dynamics and K-12 Teachers. A Lecture at the University of Virginia School of Education, Massachusetts Institute of Technology. System Dynamics Group Paper D-4665–4
27. François C (2004) *International Encyclopedia of Systems and Cybernetics*, 2nd edn. Saur, München
28. Gharajedaghi J (1999) *Systems Thinking. Managing Chaos and Complexity*. Butterworth-Heinemann, Boston
29. Harnden RJ (1989) *Technology for Enabling: The Implications for Management Science of a Hermeneutics of Distinction*. The University of Aston, Birmingham
30. Jackson MC (1991) *Systems Methodology for the Management Sciences*. Plenum Press, New York
31. Jackson MC (2000) *Systems Approaches to Management*. Kluwer Academic/Plenum, New York
32. Kauffman SA (1993) *The Origins of Order. Self-Organization and Selection in Evolution*. Oxford University Press, New York
33. Klir GJ (1969) *An Approach to General Systems Theory*. Nosstrand, New York
34. Lane DC (1994) Modeling as Learning: A Consultancy Methodology for Enhancing Learning in Management in Management Teams. In: Morecroft J, Sterman JD (eds) *Modeling for Learning Organizations*. Productivity Press, Portland, pp 205–240
35. Lane DC (1994) With a little help from our friends: How system dynamics and soft OR can learn from each other. *Syst Dyn Rev* 10(2–3):101–134
36. Lane DC (2006) IFORS' Operational Research Hall of Fame. *Jay Wright Forrester. Int Trans Oper Res* 13:483–492
37. Lane DC, Oliva R (1998) The Greater Whole: towards a synthesis of system dynamics and soft system methodology. *Eur J Oper Res* 107(1):214–235
38. La Roche U, Simon M (2000) Geschäftsprozesse simulieren: flexibel und zielorientiert führen mit Flussmodellen. Orell Füssli, Zürich
39. McCulloch WS (1965) *Embodiments of Mind*. MIT Press, Cambridge
40. Meadows DH (1980) The Unavoidable A Priori. In: Randers J (ed) *Elements of the System Dynamics Method*. MIT Press, Cambridge, pp 23–57
41. Meadows DH, Meadows DL, Randers J, Behrens III WW (1972) *Limits to Growth*. Universe Books, New York
42. Mesarovic MD, Takahara Y (1985) *Abstract Systems Theory*. Springer, Berlin
43. Midgley G (2000) *Systemic Intervention. Philosophy, Methodology, and Practice*. Kluwer, New York
44. Miller JG (1978) *Living Systems*. McGraw-Hill, New York
45. Mingers J (1997) Multi-paradigm Multimethodology. In: Mingers J, Gill A (eds) *Multimethodology*. Wiley, Chichester
46. Morecroft J (2007) *Strategic Modelling and Business Dynamics: a Feedback Systems Approach*. Wiley, Chichester
47. Odum HT, Odum EC (2000) *Modeling for all Scales: An Introduction to System Simulation*. Academic Press, San Diego
48. Pask G (1961) *An Approach to Cybernetics*. Hutchinson, London
49. Pichler F (1975) *Mathematische Systemtheorie*. de Gruyter, Berlin
50. Rapoport A (1953) *Operational philosophy: Integrating Knowledge and Action*. Harper, New York
51. Rapoport A (1986) *General System Theory. Essential Concepts and Applications* Abacus Press, Turnbridge Wells
52. Richardson GP (1999) *Feedback Thought in Social Science and Systems Theory*. Pegasus Communications, Waltham (Originally published in 1991)
53. Richmond B (1997) The "Thinking" in systems thinking: How can we make it easier to master? *Syst Think* 8(2):1–5
54. Sabelli H (2005) *Bios: a Study of Creation*. World Scientific, Hackensack
55. Schwaninger M (1997) Integrative systems methodology: Heuristic for requisite variety. *Int Trans Oper Res* 4(4):109–123
56. Schwaninger M (2004) Methodologies in conflict: Achieving synergies between system dynamics and organizational cybernetics. *Syst Res Behav Sci* 21(4):1–21
57. Schwaninger M (2006) Theories of viability. A comparison. *Syst Res Behav Sci* 23:337–347
58. Schwaninger M, Groesser S (2008) System dynamics as model-based theory building. *Syst Res Behav Sci* 25:1–19
59. Schwaninger M, Groesser S (2009) Model Validation: The Quest for Quality in System Dynamics Modeling. *Encyclopaedia of Complexity and Systems Science*. Springer, New York
60. Schwaninger M, Janovjak M, Ambroz K (2006) Second-order intervention: Enhancing organizational competence and performance. *Syst Res Behav Sci* 23:529–545
61. Schwaninger M, Pérez Ríos J (2008) System dynamics and cybernetics: A synergetic pair. *Syst Dyn Rev* 24(2):145–174
62. Senge PM (1990) *The Fifth Discipline. The Art and Practice of the Learning Organization*. Doubleday, New York
63. Shapiro M, Mandel T, Schwaninger M et al (1996) *The Primer Toolbox*. International Society for the Systems Sciences, <http://www.iss.org/primer/toolbox.htm>
64. Simon HA (1969) *The Sciences of the Artificial*. MIT Press, Cambridge
65. Sterman JD (1994) Learning in and about complex systems. *Syst Dyn Rev* 10(2–3):291–330
66. Sterman JD (2000) *Business Dynamics. Systems Thinking and Modeling for a Complex World*. Irwin/McGraw-Hill, Boston
67. Ulrich W (1983) *Critical Heuristics of Social Planning*. Haupt, Bern
68. Ulrich W (1996) *A Primer to Critical Systems Heuristics for Action Researchers*. The Centre of Systems Studies, University of Hull, Hull
69. Vennix JAM (1996) *Group Model Building. Facilitating Team Learning Using System Dynamics*. Wiley, Chichester
70. Vester F, Von Hesler A (1980) *Sensitivitätsmodell. Regionale Planungsgemeinschaft Untermain, Frankfurt am Main*
71. Von Bertalanffy L (1949) Zu einer allgemeinen Systemlehre. *Bl Dtsch Philos* 18(3/4) (Excerpts: in *Biol Gen* 19(1):114–129 and in *General System Theory*, 1968, Chapter III)
72. Von Bertalanffy L (1950) An outline of general system theory. *Br J Philos Sci* 1:139–164

73. Von Bertalanffy L (1968) General System Theory. Braziller, New York
74. Von Foerster H (1984) Observing Systems, 2nd edn. Intersystems Publications, Seaside
75. Von Foerster H (ed) (1995) Cybernetics of Cybernetics, 2nd edn. Future Systems, Minneapolis (Originally published in 1974)
76. Von Foerster H, Zopf GW (eds) (1962) Principles of Self-Organization. Pergamon Press, Oxford
77. Vriens D, Achtenbergh J (2006) The social dimension of system dynamics-based modelling. *Syst Res Behav Sci* 23(4): 553–563
78. Warfield JN (1994) A Science of Generic Design: Managing Complexity through Systems Design, 2nd edn. Iowa State University Press, Ames
79. Warren K (2002) Competitive Strategy Dynamics. Wiley, Chichester
80. Warren K (2008) Strategic Management Dynamics. Wiley, Chichester
81. Wiener N (1948) Cybernetics: Control and Communication in the Animal and in the Machine. MIT Press, Cambridge
82. Wolstenholme E (2003) Towards the definition and use of a core set of archetypal structures in system dynamics. *Syst Dyn Rev* 19(1):7–26
83. Yolles MA (1998) Cybernetic exploration of methodological complement. *Kybern* 27(5):527–542

Books and Reviews

- Jackson MC (2003) Systems Thinking: Creative Holism for Managers. Wiley, Chichester
- Klir GJ (2001) Facets of Systems Science, 2nd edn. Kluwer Academic/Plenum, New York
- Midgley G (ed) (2003) Systems Thinking, vol 4. Sage, London
- Ragsdell G, Wilby J (eds) (2001) Understanding Complexity. Kluwer Academic/Plenum, New York
- Richardson GP (ed) (1996) Modelling for Management. Simulation in Support of Systems Thinking, 2 Volumes. Aldershot, Dartmouth
- Schwaninger M (2006) Intelligent Organizations. Powerful Model for Systemic Management. Springer, Berlin
- Van Gigch JP (2003) Metadecisions. Rehabilitating Epistemology. Kluwer Academic/Plenum, New York

System Dynamics, Introduction to

BRIAN DANGERFIELD

Centre for OR & Applied Statistics, Salford Business School, University of Salford, Salford, UK

When Jay Wright Forrester published his first paper in 1958 he subtitled it “a major breakthrough for decision-makers”. At the time some thought this rather an exaggeration if not pompous. Now that 50 years of system dynamics (SD) has elapsed we can at least point to the achievements made and re-state continuing progress in

the pages of this section. Was it a ‘major breakthrough’? It certainly has the potential to raise the standards in evidence-based policy making to warrant this description and some startlingly good examples of such work will be mentioned here. But after 50 years perhaps one might expect more than has surfaced heretofore.

The key might be connected to the skills required to formulate good SD models – those which address a real-world problem with devastating simplicity and insight. It is deceptively easy to produce an SD model but there are subtleties involved in producing a really effective model for policy purposes. An uplift in modeling skills is something which a subset of the (now significant) amount of published material on SD is aimed at and this section will add to that corpus of work. In addition it will illustrate the extent to which SD applications have spread from its genesis in business to embrace health care, environmental, energy and climate issues, project management, some aspects of biological science and human physiology, governmental and public policy generally, economics (mainly macro), the diffusion of innovations and finally social and economic development. Other applications are being encountered as the power of the methodology is becoming appreciated. It has long since justified the change of title from *Industrial* Dynamics (1958) to *System* Dynamics (1970 onwards).

Richardson contributes an overview of the basics of SD modeling (see ► System Dynamics, The Basic Elements of). The underlying conceptual framework is that of the information feedback loop together with resource stocks and flows and an endogenous perspective on causation. The simplicity of the loop concept is apt to contribute to the apparent ease with which SD models can be created (along with the icon-based suites of SD software). But the novice reader should appreciate that it can take time to assimilate the modeling skills necessary to execute well an SD model-based application. Practice is essential and the references included will lead to further published material to assist the steep climb up the learning curve. So-called experts are still being confronted with the subtleties of SD modeling after years of involvement.

To place the SD methodology in context, the contribution by Schwaninger (see ► System Dynamics in the Evolution of the Systems Approach) profiles it alongside various others ‘systems’ based approaches which have emerged in the management and social sciences. Those professing to become experts in SD need to know about the other range of approaches which co-exist in the field of systems science. All these other methodologies have their own enthusiasts and this may even extend to the formation of societies with annual conferences. His Appendix B