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System Dynamics, Introduction to

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Without Abstract

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 (seeSystem 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 (seeSystem 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 shows a diagram of the different systems approaches and their interrelationships.

The foundations of the SD methodology can be characterized by certain philosophical issues. Olaya's text (seeSystem Dynamics Philosophical Background and Underpinnings) defines a central one as presentationalism, associated with the notion of 'mental models'. A number of other philosophical issues which relate to SD are introduced, including those of positivism and social theory.

The practice of SD when applied to real-world applications essentially involves managerial learning and will often involve an interaction with client teams rather than one individual. How best to organize such structured approaches to participative model building is described by Rouwette and Vennix (seeGroup Model Building). Client participation is required for successful modeling.

If the promotion of learning and understanding is the primary *raison d'etre* of SD, then achievement of this goal in an individual can be a significant accomplishment, especially if that person is the most senior in the client team. But there is a further goal to be pursued should the study fully reap the benefits of the SD methodology: How can we foster *organizational* learning? Maani tackles this head on (seeSystem Dynamics and Organizational Learning). He defines the core capabilities of a learning organization and goes on to list the developing literature on organizational learning and, most importantly, how SD can aid the process through learning laboratories and microworlds.

Running an SD model creates a time-path of output behavior covering all the variables it is deemed necessary to include in the model. The various runs of the model are, most frequently, addressed in comparative fashion rather than taken in isolation. They can therefore be described as computer-based scenarios each of which charts a possible but not assured future. Georgantzas (see Scenario-Driven Planning with System Dynamics) describes environmental (traditional) scenario generation for which there is a considerable body of literature. But he emphasizes that successful strategy design involves the integration of three things: a knowledge of the business environment; the effects of unstated assumptions about change in the environment and strategy on performance; and finally the need to *compute* the effects on organizational performance. These three facets are accomplished by the process of SD modeling.

Thus far this introductory roadmap has covered all the background for contextualizing and creating an SD model. We now turn to various tasks associated with ex post modeling activities. Three such aspects are covered: model validation; analytical methods to explain behavior and determine dominant loops; and model optimization.

Schwaninger and Groesser (seeSystem Dynamics Modeling: Validation for Quality Assurance) range over the various aspects of model validation, beginning with its epistemological foundations. In real-world modeling studies testing and validation is a sine qua non of the process. The range of tests made available and the attention given to the task of validation in the literature mark out SD as unique in the field of management science. Few other methodologies get near to the variety of tests which can be applied to an SD model. The authors consider the range of tests under three headings: model-related context; model structure; and model behavior.

Kampmann and Oliva deal with the behavioral analysis issue (see System Dynamics, Analytical Methods for Structural Dominance Analysis in). This activity tries to shed light on the model's dynamic behavior: Why does it behave as it does? What loop structures are responsible for the dominant behavior – and indeed shifts in that behavior where it occurs? In other words, they explore the link between system structure and dynamic behavior. Early methods used eigenvalue analysis but, since then, more sophisticated approaches have been put forward. A major advance will occur when one or more of these is refined enough to be included in an SD software package. This is likely to take some time although an improved user interface showing links glowing with differing degrees of intensity, reflecting their relative importance, is possible in the not-too-distant future.

Dangerfield describes the methods for improving model performance (see System Dynamics Models, Optimization of). The task can be categorized under two headings: calibration and policy optimization. The former relates to the determination of optimal parameter sets which deliver the best fit of the model to past time series data. Policy optimization on the other hand seeks to establish policies which deliver the 'best' performance against a suitable metric, such as minimum cost or maximum revenue. Using such an approach can accelerate the learning which comes from repeated runs of the model. Sadly, in the existing SD literature, there is scant evidence of its use in real-world studies.

The methodology of SD exists for no other reason than to offer a quantum leap in the standards of policy analysis. Therefore, any review must include a range through the landscape which defines areas of application. There are eight such areas covered in this section and the choice has been made in the knowledge that there are others which may also have been included and some new areas which are only just being opened up to the tools of SD modeling.

Business Strategy was the genesis of SD applications and rightly takes pride of place. This is the field in which the most numerous SD applications occur. Lyneis (see Business Policy and Strategy, System Dynamics Applications to) concentrates on the process of how SD models are used in the task of strategy formulation. He goes on to consider the various drivers of business dynamics such as oscillations in supply chains and boom and bust life cycles. Detailed references are provided for a wide range of business application case studies.

Health care is consuming a higher share of GDP in many Western industrialized countries. This is due to the age profile of the population and advances in pharmacological and medical technologies. It is unsurprising that SD methods have been applied in tackling some of the most high-profile issues in health care and the relatively recent literature is testimony to the success of SD-based analysis. Indeed, it is arguable that some of the best modeling applications have surfaced in this sector. To do justice to the field of health care two contributions were solicited, in part because of the different funding systems which exist on either side of the Atlantic: Wolstenholme surveys the work done by UK and European authors (see Health Care in the United Kingdom and Europe, System Dynamics Applications to), whilst Hirsch and Homer concentrate on work published by US authors (seeHealth Care in the United States, System Dynamics Applications to).

Wolstenholme describes work carried out in the UK and Continental Europe but gives particular emphasis to three areas where models have been deployed. He starts with the problem of delayed hospital discharge which generates hospital capacity problems. Epidemiology is also reviewed, in particular research on the epidemiology of HIV/AIDS. Finally, recent work on mental health reform in the UK is described.

Hirsch and Homer note that the system in the USA is comparatively difficult to manage because of its free-market approach and relative lack of regulation. They concentrate on three main areas: disease epidemiology including heart disease and diabetes; substance abuse; and health care capacity and delivery.

Along with health care, the depletion of environmental resources and its effects has consumed many thousands of column inches in printed news media. SD has been employed in the pursuit of more compelling applications in this sector and the efforts go back to the well-known *Limits to Growth* study in 1971–72. Ford charts the most notable efforts which have emerged (seeSystem Dynamics Models of Environment, Energy and Climate Change). He ranges over environmental resource problems in the western USA, models for greater understanding of climate change and global warming and concludes with studies in energy, specifically two applications to the electric power industry.

The field of economics is one where SD has received a mostly hostile reception. The statistical economic modeling tool of econometrics has an extensive history and as a preferred modeling methodology seems hard to dislodge. However, there are an increasing number of heterodox economists who are prepared to embrace SD concepts and Radzicki (seeSystem Dynamics and Its Contribution to Economics and Economic Modeling) describes the advances taking place. Whilst some of the literature embodies the translation of existing economic models into an SD format (which is a laudable objective) he calls for more economic dynamics models to be built from scratch embodying the best practice in SD modeling. Economic policy is too important to be informed by a single, seemingly unassailable, modeling methodology and it is to be hoped that in the future SD will become even more accepted as a viable tool for use in this field.

In a similar vein comes the contribution of Saeed (seeDynamics of Income Distribution in a Market Economy: Possibilities for Poverty Allevation). He takes an economic modeling perspective and describes an SD model which explains resource allocation, production and entitlements in a market economy. Its purpose is to understand better how poverty might be reduced in the context of the redistribution of income. A comprehensive listing of the model is provided in an appendix.

The application of SD to public policy generally is dealt with by Andersen, Rich and MacDonald (seePublic Policy, System Dynamics Applications to). They emphasize how public policy issues are complex, cross organizational boundaries, involve stakeholders with widely different perspectives and evolve over time, such that longer term results may be wholly different from short-term outcomes. Detail is provided for one public policy case involving the Governor's Office of Regulatory Assistance in New York State. They conclude with coverage of studies in a range of public domains such as defense, health care, education and the environment.

One area of SD application has brought the methodology into the legal arena. Disruption and delay in the execution of complex projects invariably finds two parties in dispute. Such disputes often center upon time delays and use of resources on projects – and what might have happened if things had been managed differently. SD models have been employed by parties to such disputes to attempt to justify the occurrence of these events. Howick, Ackermann, Eden and Williams (seeDelay and Disruption in Complex Projects) report on how cognitive mapping, cause mapping and SD can be fused into what they describe as a cascade model building process. The result is a rigorous process for explaining why a project behaved in a certain way.

New products and processes are emerging at an ever-increasing rate in modern times. We need to understand the myriad mechanisms which are the basis for their rate of adoption. Milling and Maier range over various SD models which have been created to understand and improve the management of the diffusion of innovations (seeDiffusion of Innovations, System Dynamics Analysis of the). From the often-cited Bass diffusion model (1969) the authors develop a series of additional features in a modular fashion. These features include competition, network externalities, dynamic pricing and research and development. They conclude by stressing how it is not possible to offer general recommendations for strategies in dynamic and complex environments; such recommendations can only be given in the context of the specific case under scrutiny.