MENTAL MODELS OF DYNAMIC SYSTEMS

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Contents

Summary

Mental models play a central role in system dynamics efforts to improve learning and decision making in complex systems. In fact, the system dynamics methodology can be generally described as a feedback process in which mental models are used to develop a computer model, which in turn creates new opportunities for learning that improve the accuracy, coherence, and complexity of mental models. This article describes the history of the mental models concept in the fields of system dynamics and psychology, and offers a comprehensive definition of the term for use in system dynamics research. The characteristics of mental models of dynamic systems identified by the empirical literature are reviewed, with an emphasis on important flaws and limitations, as well as their underlying causes, which typically limit the utility of mental models for dynamic decision making. A mental model-based theory of dynamic decision making is presented that is consistent with this evidence, and the mechanisms by which system dynamics computer modeling can improve mental models within this theoretical framework are described. The implications of the theory for developing appropriate

techniques for studying mental models, as well as specific priorities for future research, are discussed.

1. Introduction

The idea that human minds create, store, and manipulate internal models of the dynamic systems with which they interact has been central to the theory and practice of system dynamics since its inception. The nature and properties of these mental models in fact provide the primary rationale for the need to employ system dynamics modeling to improve learning and decision making in the face of complexity. According to the system dynamics view, people can (and should) manage systems by constructing a mental model and mentally simulating it to determine the likely outcomes of policy decisions. Learning occurs by comparing expectations with the actual observed consequences of policy decisions and using this outcome feedback to revise or update the mental model.

However, both practical experience in the field of system dynamics and controlled laboratory experiments on dynamic decision making have shown that mental models of complex systems are typically subject to a variety of flaws and limitations. For example, mental models often omit feedback loops, time delays, and nonlinear relationships that are important determinants of system behavior. In addition, the limited capacity of working memory makes it impossible for people to mentally simulate the dynamic implications of all but the simplest mental models. According to the system dynamics view, only by adopting the feedback perspective and modeling discipline of system dynamics and taking advantage of the computer's ability to calculate the dynamic consequences of mental models can these flaws and limitations be overcome.

Despite the known flaws and limitations of mental models, they are often tapped as a primary source of information for system dynamics model building. A system dynamics modeling project typically begins with an effort to elicit or externalize the mental models of policymakers, so that they can be shared and submitted to a process of scrutiny and evaluation.

There are several advantages to such an emphasis on mental information to supplement the written and numerical databases that are vitally important to all approaches to modeling systems, including system dynamics. First, the mental database that people form through observation and experience is vastly larger than the other databases. Only a fraction of the knowledge people gain during their lives is ever written down, and an even smaller percentage of what is written is expressed numerically. Second, the mental database is more likely to contain the type of information that is needed to build system dynamics models, namely, the details of system structure and the cognitive processes by which managers make decisions. Third, the mental database can be more easily probed, and can provide information that allows modeling to proceed when written and numerical information is absent. Fourth, the elicitation and use of mental data allow managers to develop a sense of ownership of the resulting model, as well as to gradually see their own mental models revised and transformed, both of which aid learning and increase satisfaction with the modeling process.

The main disadvantage with the use of mental data in model building, of course, is the increased potential for errors and biases, since the data have not been subject to the editorial or review processes that are typical of written and numerical data. System dynamics practitioners acknowledge this potential for error in data collection and have developed knowledge elicitation procedures that attempt to minimize it. Furthermore, they argue that the mental database is not so flawed that it cannot serve as a useful starting point for modeling, and that the iterative nature of the modeling process will eventually uncover the important errors that do exist.

Given the importance of mental models for improving dynamic decision making and as an information source for model building, it is not surprising that system dynamics researchers have devoted an increasing amount of their research effort in recent years to their study. System dynamics practitioners have developed a variety of diagramming techniques for representing mental model information in ways that promote learning (see *Knowledge Elicitation*). They have also developed substantial practical experience in the design and implementation of group facilitation and group model building programs to change mental models and improve decision making (see *Group Model Building*). In recent years, efforts have increased to validate this practical knowledge about measuring and changing mental models through rigorous experimentation and assessment.

2. Definition

Despite its role as one of the most important concepts in system dynamics, the term “mental model” is also one of the least well defined. To some degree this is due simply to the inherent difficulties of defining any mental concept. Mental models are not directly observable, and their character must be inferred from observations of overt human behavior. They are also subject to what one system dynamics research group has termed “the mental model uncertainty principle,” which states that the mere act of trying to understand or measure them may itself alter mental models. There is the added difficult that researchers themselves must rely on potentially flawed or biased mental models while struggling to identify their character.

A second reason for the difficulty of system dynamics researchers in establishing a mutually agreeable definition of mental models is the checkered history of the concept.
Since its first use by the psychologist F.I.M. Craik in his 1943 book *The Nature of Explanation*, the term mental model has taken on a variety of meanings, all of which are still in current usage. For example, in psychology and related fields, mental models have been variously referred to as mental diagrams or picture-like images, mental representations, intuitive theories, collections of beliefs, schemas, and knowledge networks. In system dynamics, Jay Forrester introduced the term to the field in his seminal work *Industrial Dynamics* in 1961, stating that mental models are “mental images or verbal descriptions…[that] substitute in our thinking for the real system that is represented.” In the intervening decades, system dynamics researchers have at times described mental models as intuitive generalizations, collections of ideas, opinions and assumptions, networks of facts and concepts, and implicit causal maps of systems.

A recent effort by two of the present authors (Doyle and Ford) to synthesize existing ideas into a useful form for system dynamics research and practice resulted in the following conceptual definition:

A mental model of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external system (historical, existing, or projected) whose structure is analogous to the perceived structure of that system.

In this definition, the phrase "relatively enduring" implies that a mental model, while subject to changes that occur on the order of minutes or seconds, may persist in long-term memory in some form for years or decades. The word "accessible" suggests that people are generally consciously aware of their mental models and to a large degree can mentally inspect them and communicate them to others. "Limited" means that the term mental model should not refer to all of the knowledge held by an individual but to a precompiled subset of information in long-term memory. The maximum size of a mental model is determined by the capacity of working memory, the mental workbench on which people store information temporarily while thinking about it. Since the amount of information that can be organized into a meaningful grouping of information (or chunk) in working memory is flexible, the maximum size of a person's mental model may increase to some degree as they gain expertise and learn to organize information more efficiently. However, no amount of experience or expertise can alter the maximum number of chunks. Due to such unalterable cognitive limitations, it is not surprising that, as Jay Forrester, the founder of the field of system dynamics, has remarked, most mental models are usually no more complex than "a fourth-order differential equation."

The term "internal" in this definition indicates that mental models are cognitive phenomena, that is, they exist only in the mind and they should not be confused with the results of efforts to "elicit," "surface," "map," or "measure" mental models due to the strong possibility of measurement error or bias. The word "conceptual" restricts the definition of mental models, for system dynamics purposes, to models composed of symbols, concepts, ideas, or other language-like components rather than mental imagery. The phrase "representation of an external system" implies, first, that mental models are cognitive structures that store information, rather than cognitive processes which transform information, and second, that mental models refer to or represent objects, processes, information, or mental constructs that are outside the boundary of the mental model. The use of the term "structure" implies that mental models are not simply knowledge but knowledge that has been organized and interconnected in some way.

Finally, it should be noted that the word "perceived" in the final phrase of the definition is important to make it clear that an individual's mental model of a system may or may not bear a resemblance to the real system, depending on the accuracy of their perception. The field of system dynamics has yet to converge on a widely agreed upon definition of mental models, which is not surprising given the ethereal nature of mental models and the inherent difficulties of studying them. The above-stated definition, although the most comprehensive available, should not be considered to be correct or complete but merely a useful starting point for further refinement and debate.

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Bibliography

Axelrod R., (ed.) (1976). *The Structure of Decision: The Cognitive Maps of Political Elites*. Princeton, NJ: Princeton University Press. [A classic work that employs content analysis techniques to understand the mental models underlying political decision making.]

Doyle J.K. (1997). The cognitive psychology of systems thinking. *System Dynamics Review* **13**(3), 253–265. [This paper describes the need for rigorous controlled research on the effect of system dynamics modeling on mental models and cognitive processes.]

Doyle J.K., and Ford D.N. (1998). Mental models concepts for system dynamics research. *System Dynamics Review* **14**(1), 3–29. [This paper contains the most comprehensive definition of mental models of dynamic systems currently available.]

Gentner D. and Stevens A.L., (eds.) (1983). *Mental Models*. Hillsdale, NJ: Elrbaum. [An important collection of empirical papers on mental models of simple physical systems.]

Johnson-Laird P. (1983). *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness*. Cambridge, MA: Cambridge University Press. [This classic book presents a mental-model based theory of logical reasoning.]

Richardson G.P., Anderson D.F., Maxwell, T.A., and Stewart T.R. (1994). *Foundations of Mental Models Research*. (Proceedings of the 12th International System Dynamics Conference, Stirling, Scotland, 11-15 July). [This paper offers perhaps the most detailed theoretical statement on the role of mental models in dynamic decision making currently available.]

Rips L. (1986). Mental muddles. *The Representation of Knowledge and Belief* (eds. M. Brand and R.M. Harnish), pp. 258–286. Tucson, AZ: University of Arizona Press. [An important critique of the mental-models approach to decision making and problem solving.]

Rouse W.B. and Morris, N.M. (1986). On looking into the black box: prospects and limits in the search for mental models. *Psychological Bulletin* **100**(3), 349–363. [A useful review article of mental models research in human-computer interaction with lasting relevance.]

Sterman J.D. (1994). Learning in and about complex systems. *System Dynamics Review* **10**(2/3), 291–330. [This paper presents a compelling and detailed explanation of the need for and benefits of system dynamics modeling to improve mental models and dynamic decision making.]

Vennix J.A.C. (1990). *Mental Models and Computer Models: Design and Evaluation of a Computer-Based Learning Environment for Policy-Making*. Den Haag: CIP-Gegevens KoninklijkeBibliotheek. [This book describes what is perhaps the most rigorous, detailed empirical study of changes in mental models of dynamic systems ever attempted.]

Biographical Sketches

James K. Doyle is an Associate Professor of Psychology in the Department of Social Science and Policy Studies at Worcester Polytechnic Institute. He earned his Ph D. in Social Psychology, with a minor in Cognitive Psychology, from the University of Colorado at Boulder, where he conducted research on risk perception at the Center for Research on Judgment and Decision Making, Institute of Cognitive Science. His work has appeared in *Risk Analysis, the Journal of Applied Social Psychology*, and *the System Dynamics Review*, among other journals. His current research interests focus on the interface between psychology and system dynamics, in particular mental models theory and measurement, knowledge elicitation for model building, and evaluation of efforts to improve thinking and learning about complex systems. Dr. Doyle is a member of the American Psychological Society, the Society for Judgment and Decision Making, and the System Dynamics Society and is an associate editor of *the System Dynamics Review*.

David N. Ford is an Assistant Professor in the Construction Engineering and Management Program in the Department of Civil Engineering, Texas A&M University. Dr. Ford earned his Ph.D. degree from the Massachusetts Institute of Technology and his Master and Bachelor's degrees in Civil Engineering from Tulane University. He researches development project strategies, processes, and resource management and teaches. Prior to his appointment at Texas A&M Dr. Ford was a member of the faculty of the Department of Information Science at the University of Bergen, Norway, where he researched and taught in the System Dynamics Program. Dr. Ford's work has been published in the ASCE *Journals of Construction Engineering and Management* and *Management in Engineering, Construction Management and Economics, the Journal of Applied Behavioral Science*, and *System Dynamics Review*. His current research interests include the application of real options to construction planning, overbooking in professional service firms, and construction management mental models. He has over 14 years of industry and government experience in civil engineering and project management and is a registered professional engineer.

Michael J. Radzicki is an Associate Professor of Economics at Worcester Polytechnic Institute in Worcester, Massachusetts. He received his Ph.D. in economics from the University of Notre Dame and his training in system dynamics modeling from the Massachusetts Institute of Technology. Professor Radzicki's research areas include economic methodology and macroeconomic dynamics, and he is currently developing a system dynamics model of the United States economy based on post-Keynesian economic theory. He has served on the editorial boards of *the Journal of Economic Issues*, *the System Dynamics Review*, and *the Systems Thinker*, and as both vice president and secretary of the System Dynamics Society. In addition to his work in economics and system dynamics, Professor Radzicki is an avid long distance runner, motorcyclist, and a black belt instructor in Shaolin Kempo Karate.

W. Scott Trees is a Professor of Economics and Chair of the Economics Department at Siena College. He received his Ph.D. from the University of Notre Dame. His research interests include the economics of poverty; alternative methodologies and their contribution to our understanding of policy issues; sustainable agriculture; and mental model theory and measurement. Recent projects have included grants to study both community-supported agriculture in the United States and the impact of IMF policy on poverty in developing countries.