Mental Load

► Mental Effort

Mental Logic

► Schema-Based Reasoning

Mental Model Convergence

► Learning-Dependent Progression of Mental Models

Mental Model of Dynamic Systems

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Synonyms

Mental models of dynamic systems, MMDS

Definition

Cognitive processes are any mental activity that acquires, stores, transforms, reduces, elaborates, or uses knowledge. Cognitive processes are also referred to as cognition.

Dynamic decision making is the process of assessing and choosing among alternatives at different times in the course of managing a dynamic system, that is, an environment that changes over time.

A *dynamic system* is one whose state changes with time. Dynamic systems are relevant to describe dynamic phenomena in many fields of research, for instance, in psychology, operations research, management, political sciences, sociology, and economics.

Model-based learning (MBL) refers to the activity of humans interacting with an external, formal model for the purpose of learning. The external model is used as a point of reference that structures and guides the learning process with the learner.

Model is a simplified representation of a real system. Models appear in this entry in the form of external and internal models. An *external model* is an explicit, mostly graphical representation of an internal (mental) model of an individual. It provides a means for communication and analysis. An *internal* (*mental*) *model* is a construct of cognitive psychology. Mental models are internal representations of conceptual and causal interrelations among elements that people use to understand phenomena.

Feedback is the transmission and return of information about the current output condition of a system. A *feedback process* is a process by which a system is controlled or changed by the output or response it produces.

Learning is considered a feedback process of the following kind: Our decisions alter the real world, we receive information feedback about the world and revise the decisions we make and subsequently the mental models that motivate those decisions. Learning can also be seen as a process of discovering the content and structure of a model or reality.

A *stock and flow diagram* (SFD) is a tool for graphically representing mental models of dynamic systems. Such a diagram is a means to represent the feedback structure of a system that consists conceptually of feedback loops.

System Dynamics is a computer modeling methodology that is used to represent and analyze complex nonlinear dynamic feedback systems for the purpose of generating insights and improving system performance. It has its intellectual origins in control theory, management science, and digital computing. It was created in 1957 by Jay W. Forrester of the Massachusetts Institute of Technology as a method for helping managers better understand and control corporate systems. Today, it is applied to topics in a wide variety of academic disciplines; see www.systemdynamics.org and the journal "*System Dynamics Review*."

Theoretical Background

Relevance of Mental Models of Dynamic Systems

It has been argued that today's world becomes ever more complex, interconnected, and dynamic.

Incremental and radical innovations are occurring at increasing rates in all pertinent areas of life with significant impacts. Because of this, human actions lead to counter-actions by others resulting in resistance against the original intention. In principle, the performance of activities is a process based on feedback, adaptation, and subsequent learning which is guided by the individual's mental models. A mental model reflects an individual's beliefs, values, and assumptions. It forms the reasons for actions. More formally, a mental model is an internal conceptual representation of causal interrelations among elements that people use to understand and manipulate reality.

Learning is essential for performance in reality. It is, in principle, a feedback process in which our decisions influence the real world, as a result of which we receive information feedback about the world and revise both the decisions we make and the mental models that motivate those decisions. However, experimental research demonstrates that people have a very poor understanding of even the simplest dynamic systems (Sterman 1994). In other words, their mental models of dynamic systems (MMDS) are not elaborated enough to capture the essential aspects of those dynamic systems. This is because learning in dynamic systems is constrained by several factors: The failure to register outcome feedback, ambiguous causal understanding, systematic misperception of feedbacks, nonlinearities, and time delays. To develop more useful and accurate MMDS, methods for enhancing learning about dynamic systems must overcome these impediments. Model-based learning with System Dynamics is one such method to address this (see Groesser, ► Model-based Learning with System Dynamics in this issue). The improvement of MMDS is of the highest relevance, since managerial and political decision making can be highly biased when the basic dynamics are not understood (e.g., Sterman 2008).

General Shortcomings of Mental Models

Mental models are theoretical concepts. They try to represent the cognition of an individual, that is, an individual mental model, or of a group of individuals, that is, a team mental model. Mental models are incomplete, overly simplistic, unstable, and highly flexible and thus inconsistent over time, ambiguous, and often open-loop models with narrow boundaries. These are some of the characteristics of mental models which have also been addressed by Herbert Simon with his principle of bounded rationality (Simon 1982).

Definition of Mental Models and the Mental Models of Dynamic Systems

Mental model research was first used by the psychologist K. J. W. Craik in his 1943 book, *The Nature of Explanation*. Since then, the term "mental model" has taken on a variety of meanings, all of which are still in usage. In psychology, for instance, mental models have been used as mental diagrams, mental representations, collections of beliefs, schemas, and knowledge networks. One current understanding of mental models in psychology is that a mental model consists of two or more assertions which are linked together. An assertion is a statement about a fact or a statement about the logical relationship between facts (Seel 2001).

Doyle and Ford (1998, 1999) have introduced the concept of a MMDS as an understanding of mental models that is more specific than previous mental model definitions. Groesser and Schaffernicht have provided an operational definition: "A mental model of a dynamic system is a relatively enduring and accessible, but limited, internal conceptual representation of an external dynamic system (historical, existing, or projected). The internal representation is analogous to the external system and contains, on a conceptual level, reinforcing and balancing feedback loops that consist of causally linked stocks, flows, and intermediary variables. The causal links are either linear or nonlinear, and can be delayed." (Groesser and Schaffernicht resubmitted, p. 22).

Relation Between Mental Models and MMDS

In the following, the relation between previous mental models and MMDS is provided. In principle, a MMDS is an instance of a mental model with special properties. The most important difference is that mental models in the previous notion are open-loop models, that is, models without any particular notion of feedback relations. A MMDS, on the other side, emphasizes the concept of closed-loop or feedback relations. This difference is essential because in an individual's open-loop mental model the dynamics arise from exogenous events, whereas in a closed-loop MMDS the dynamics emerge internally. A second difference occurs when there is more than one reason for an outcome to occur. In this case, the outcome is possibly explained by the existence of several mental models in parallel. From the perspective of MMDS, only one MMDS exists which encompasses all of the possible partial explanations for the outcome. The relative importance of the different partial explanations can vary, but the MMDS is a comprehensive representation of the individual's understanding of the situation.

Conceptual Structure of a MMDS

A conceptual structure of a MMDS, as shown in Fig. 1, shows the constituent elements in its framework. We can see a hierarchy in these elements, beginning with a feedback loop at the highest level. Feedback loops consist of the underlying elements, that is, variables and causal links. They are closed chains of causal relations which return information about the current output condition of a system to its input. A feedback loop has either a positive or a negative polarity. The former reinforces initial changes of a variable in the feedback loop; the latter counteracts changes in a variable within the feedback loop.

Variables constitute the second major group of conceptual elements. Variables can be conceived of as the knots in a network. Three types of variables are differentiated: Stocks, flows, and auxiliaries. Stocks describe the current condition of dynamic systems. They are accumulations of resources which can be measured directly (e.g., material, financial resources) or only indirectly (e.g., attitude, motivation). Flows, or flow rates, describe how stocks change over time, that is, flows are the means to change stocks. Auxiliary variables are neither stocks nor flows; they are intermediate variables which are used to formulate flow variables.

Causal links are the relationships between variables, that is, they are the connections between the knots in the network. They have three properties: Polarity, delay, and the shape of a relationship. The polarity, as in the case of a feedback loop, can be either positive or negative. For a positive polarity, an increase in the quantity of variable A leads to a subsequent increase in the quantity of variable B above the level it otherwise would have had (and vice versa for an initial decrease). Given an initial increase in the quantity of variable A, a negative polarity leads to a decrease in the quantity of variable B below the level it otherwise would have had (and vice versa for an initial decrease). A delay in a link indicates if the causal relationship is directly coupled in time (no delay) or if the effect lags the initiating cause by some interval. The shape of relationship between variables A and B can be either linear, that is, a change in variable A leads always to the same change in variable B, or nonlinear, that is, that a change in variable A leads to different changes in the variable B conditional on the current value of variable A. After defining the conceptual structure of a MMDS, the representation thereof is shown next.

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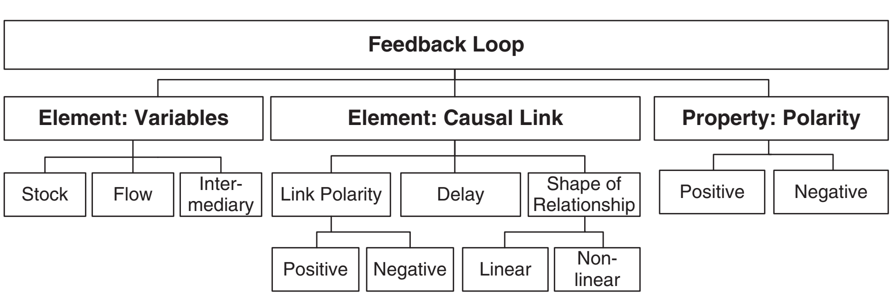
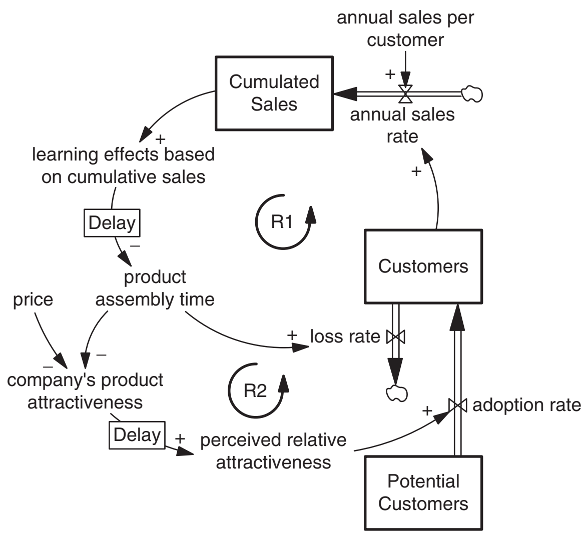
Representation of MMDS

Conceptually, MMDS consist of the structure as outlined in Fig. 1. Using this structure, the MMDS of an individual can be expressed. What is required is a representation method which is potent enough to account for all elements of the conceptual structure. A stock and flow diagram (SFD) is the method which best fulfills this purpose. Another frequently used method is a causal loop diagram.

In a SFD (Fig. 2), feedback loops are identified by R and B – R indicates reinforcing feedback loops,



Mental Model of Dynamic Systems. Fig. 1 Conceptual structure of mental models of dynamic systems (Groesser and Schaffernicht resubmitted)



Mental Model of Dynamic Systems. Fig. 2 Mental models of dynamic systems can be represented as system structure diagram

B would indicate balancing feedback loops. Stocks, which represent accumulations, are shown as rectangles (customers, potential customers); flow rates (adoption rate, loss rate, annual sales rate) cumulated sales are directly connected to the stocks. The remaining variables are auxiliary variables. Causal links between the variables are shown as arrows. The polarities of the links are assigned at the arrowhead (+ or −). Delays are represented by a box labeled with "Delay" (e.g., between a company's product attractiveness and its perceived relative attractiveness).

In the SFD in Fig. 2, the logic of an individual about the production and sales mechanisms of a company is shown. According to the thinking of this individual, customers who buy the products create sales for the company. The increasing number of products sold fosters accumulations in experience and learning about production and production management. This, in sequence, results in reduced assembly times, a fact which customers appreciate. Consequently, customers are more loyal to the company, thus leading to a lower loss rate. In addition, the higher availability of the products increases its attractiveness on the market. This is registered by potential customers with a perception delay. After this time lag, potential customers adopt the product, resulting in an increased customer stock. The owner of the MMDS perceives two reinforcing feedback loops (R1 and R2). It is obvious, however, that the MMDS is incomplete. For instance, the "perceived relative attractiveness" is a concept which is also influenced by other products available on the market. This is, however, currently not an element of the individual's MMDS. This MMDS example should clarify how a SFD is used to present the MMDS of individuals or teams. For more information on SFD, refer to Sterman (2000) and the literature cited therein.

Important Scientific Research and Open Questions

Research about MMDS is relatively new but nevertheless aspiring. It addresses among others the following questions: How are MMDS measured? How do MMDS change over time? Why is it that people who have relatively elaborated MMDS sometimes fail to apply them? Research about these topics is undertaken by experts specialized in Psychology and/or System Dynamics, for example, at the Worcester Polytechnic Institute, USA. (www.wpi.edu), at the University of St. Gallen, Switzerland (www.systemdynamics.ch), at the Universidad de Talca, Chile, and at the University of Bergen, Norway (www.uib.no/rg/dynamics). In the following, relevant research areas are outlined and briefly treated.

Conceptual Structure, Measurement, and Elicitation of MMDS

The comprehensive but parsimonious conceptual structure of a MMDS has been detailed in a previous section. The next step is to develop measurement scales and elicitation procedures to operationalize the conceptual structure. The difficulty, however, is that the mere act of trying to measure and understand MMDS might already alter the model itself. This fact leads to additional uncertainty in the measurement of mental models. Research about measurement and elicitation must use methods that are as naturalistic as possible, that is, that correspond to the settings, tasks, and question formats that people normally deal with when they think about dynamic systems (Doyle et al. 2008). Moreover, it becomes important to use elicitation methods that do not impose a particular structure, but allow the substantive structure to arise from the subjects' responses.

Evolution of MMDS

External representations of MMDS are only a snapshot of an individual's cognition at a specific point in time.

Changes of a MMDS can occur both over short and long periods. In principle, it is possible to compare the subsequent changes (Schaffernicht 2006). Schaffernicht and Groesser (2011) have developed a method of comparing MMDS which builds on and enhances previous measurement approaches (Langfield-Smith and Wirth 1992; Markóczy and Goldberg 1995).

Improving MMDS and the Results in Decision Making

Indications suggest that it is possible to enhance MMDS especially by the use of Model-based Learning with System Dynamics. By this means, it is possible to make mental models more complete, coherent, complex, dynamic, and feedback oriented. It is argued that the process of Model-based Learning with System Dynamics facilitates improving the learner's mental models by engaging in inquiry that is otherwise impractical or even impossible. Through the use of such tools, the cost in time and resources for learning iterations is reduced. Thus, the number of iterations can be increased, resulting in a potentially more detailed understanding of the problem at stake. In addition, Model-based Learning with System Dynamics can reveal the dynamic complexity of the systems; untangle inadequate and ambiguous outcome feedback; and can help to overcome misperceptions of feedback. By this process, MMDS can be elaborated. This has been shown by recent studies. For instance, Capelo and Dias (2009) conclude that learning interventions with System Dynamics computer simulations can lead to a higher degree of similarity among the mental modes of the decision makers. Sterman (2010) confirms that an education in System Dynamics is helpful in improving dynamic decision making. However, some well-documented cases exist in which improved MMDS failed to lead to better decisions. More research is required, therefore, to identify the contingencies under which both improving and utilizing improved MMDS can occur.

From Individual MMDS to Team MMDS

A further research avenue is the measurement and development of team mental models. Since research about MMDS is relatively new compared to research about common mental models, not many studies exist in this respect. It is advisable that research about team MMDS draw on existing studies of team mental models (e.g., Lim and Klein 2006; Mohammed et al. 2010).

In general, publications in recent years have shown an upward trend leading to a significant increase in the analysis of MMDS.

Cross-References

► Computer Simulation Model
► Dynamic Modeling and Analogies
► Mental Models
► Model-Based Learning with System Dynamics
► Feedback and Learning
► Simulation and Learning: The Role of Mental Models
► Simulation-Based Learning

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Mental Models

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Synonyms

Cognitive model representation; Internal model; Working model

Definition

Along with other types of cognitive structure, mental models are representations in the human mind of various aspects of an individual's lifetime experiences. Mental models are internal representations containing meaningful declarative and procedural knowledge that people use to understand specific phenomena. People can construct mental models in order to explain or to simulate problems, events, or future situations in mind, if no sufficient *schema* is available. A scientific analysis of mental models is very useful to optimize learning processes but depends on some preconditions. For example, an important precondition is an adequate measurable externalization of mental models. Another precondition is *consciousness* of knowledge which might be relevant for constructing a model.

Theoretical Background

Although mental models are often considered as a major theoretical construct of modern cognitive science closely related with the issue of knowledge representation (Markman 1998), the idea of mental models has a long tradition in the twentieth-century psychology and epistemology in which various roots can be distinguished. In accordance with neopragmatism and constructivism, mental models are widely defined as the mind's internal representations of real, hypothetical, or imaginary world phenomena. Usually, the idea of mental models is traced back to Kenneth Craik (1943), who argued that the mind constructs "small-scale models" of reality to anticipate events, to reason, and to underlie explanations. In other words, an individual who intends to give a rational explanation for something must develop practical methods in order to generate adequate explanations from knowledge of the world, using limited capacities for information processing in doing so. Thus, in order to create situation-specific plausibility, one individual constructs a *model* that integrates the relevant semantic knowledge and meets the requirements of the situation to be mastered. This model "works" when it is within the realm of the subject's knowledge as well as the explanatory need with regard to the concrete learning situation to be mastered cognitively. Like pictures in Wittgenstein's "picture" theory of the meaning of language, mental models have a structure that corresponds to the structure of what they represent. Since Craik's seminal work, cognitive scientists argue that the mind constructs mental models as a result of perception, imagination and knowledge, and the comprehension of discourse.

Parallel with emerging cognitive science, similar conceptions of internal or mental models have been adapted by scientists who were concerned with the pragmatic aspects of modeling (Stachowiak 1973) or the psychological investigation of experts operation with complex technical or physical systems (Veldhuyzen and Stassen 1977). Action regulation approaches consider mental models as the basis for mental simulations, anticipations, and regulation of actions. In addition, the conception of internal models also played a central role in information science in the 1950s and 1960s. Here, learning was considered as a complex procedure of constructing internal models of the environment (Steinbuch 1965) that were conceived as cognitive isomorphisms of structured domains of the environment.

Despite these early approaches, the concept of mental models became very influential in cognitive