An Overview of System Dynamics Methods for Developing Management Flight Simulators

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Abstract: This paper presents an overview of the System Dynamics methods and the existing knowledge and practices for the development Management Flight Simulators. Management Flight Simulators constitute the ultimate cybernetic method for learning and testing strategies prior to implementation. The main issues and trends in the field are identified, and new views to the development of System Dynamics simulation models are suggested. Having gone through a review process of relevant sources, a conceptual framework for the development of System Dynamics Management Flight Simulators is proposed. The proposed framework would be particularly useful for researchers in the field but also for practitioners and developers of decision support systems.

Key-Words: System Dynamics, Management Flight Simulators, microworlds, modeling and simulation, cybernetics

1 Introduction

All businesses, ranging from conventional organizations, e-commerce enterprises, are faced with complex strategic and operational decisions due to an increasingly dynamic economic environment and accelerating social, economic and technological change. In this context of uncertainty and complexity, it is impossible to make perfect decisions and find optimal solutions for a given problem. Therefore, managers rely on their experience, rules of thumb, formal hierarchies, existing organizational procedures or simply intuition when making decisions. Our rationality in making decisions is very much limited by our processing capabilities. As Sterman (2000) [1] stated people mostly act in the continuum between perfect rationality and mindless, capricious behavior. And our intention to solve a problem may result in unforeseen side effects causing even more problems. Sterman (2001) [2] called this effect "policy resistance", which is due to human mental model limitations to comprehend the systemic effects.

This is where System Dynamics comes in to put the diverse pieces of the system together. System Dynamics can be used as the modeling method for creating Management Flight Simulations, also called "microworlds" – a concept first defined by Papert in 1980. Microworlds help its users "in practice" to understand the dynamic behavior of complex physical, biological, and social systems and helps managers and policy makers learn and make more effective decisions on policy design and organization. The simulation environment created by microworlds compresses time and space for the decision maker to be able to understand a complex system, see the long-term effects of our decisions, learn faster, and design more successful strategies.

2 System Dynamics and Management Flight Simulators

A Management Flight Simulator can be a board game or a physical model, but for a complex dynamic system there is only one form – a computer simulation game. Simulation games are very effective tools in identifying time delays of the existing systems and their long and short term effects on an organization, by enabling users to increase or decrease the time delay in the game environment and see the changes it would produce over time. "Flight simulators" can compress time, enabling decade-long scenarios run in a matter of seconds on the desktop. In the same way organizational feedback loops (communication paths) can be reproduced in a computer simulation environment, and the effects of their modification or removal evaluated. Thus a system or a set of policies get to be tested without the real consequences and expenses.

Properly constructed computer simulations have the power to challenge our mental models, making us aware of possible unintended outcomes of our actions. They also help us test how various factors can improve organizational efficiency and effectiveness in situations where it is not possible to perform a real-world experiment. As expressed by De Geus (1992, p.3) [3], addressing the management of organizations: “By computer modeling their world, we give managers a ‘toy’ (a representation of their real world as they understand it) with which they can ‘play’, i.e. with which they can experiment without having to fear the consequences”.

2.1 System Dynamics

Management Flight Simulators use Systems Dynamics as a conceptual tool. Thus, the first step of literature review was to find what System Dynamics is and how it has developed over time.

The birth of System Dynamics is marked by Jay W. Forrester’s of the Massachusetts Institute of Technology “Industrial Dynamics” book published in 1961 (Forrester, 1961) [4]. Forrester defined System Dynamics as the study of industrial activity’s infromation-feedback characteristics, which aims to show how the structure of an organization, policy amplifications and action time delays interact, which influences performance of the whole organization. Forrester was the first to show how System Dynamics treats the interactions between various flows such as money, materials, personnel, information, equipment, etc. in an industry, company, or economy. The symbols used by Forrester to depict the stocks or levels and flows or rates of change were taken from the Feedback Control theory. The high complexity of Forrester’s stock-flow diagram, led to the creation of hybrid diagrams, a mixture of both causal and flow diagrams, but closer to the causal diagrams (Richardson, 1991) [5].

Since then the concept of System Dynamics did not undergo many vital changes, except that now it is applied mostly in an Information Technology context and its definition can be narrowed down to: a method for solving problems by computer simulation. Unlike Systems Thinking or Systems Analysis, System Dynamics is based upon quantitative computer simulation models for strategic decision making, and feedback thinking. System Dynamics is used for modeling complex feedback systems characterized by multiple decision feedback loops, delays, and nonlinearities.

System Dynamics was first applied for the study of industiral and economics systems. From the begining System Dynamics became an attractive topic and there was a wide variety of System Dynamics areas that recearchers from all over the world began to develop. Some of them are: Urban and Public Policy Dynamics, started by Forrester in his paper “Urban Dynamics” (Forrester, 1969) [6]; Global Modelling, as introduced by Meadows *et al.* (1972) [7]; in 1985 Sterman wrote his first paper on Economic Modelling (Sterman, 1985) [8], which was a base of STRATAGEM-2 game, testing the decision rules rationality; other papers were validating and further formulating the System Dynamics Models, as done by Morecroft (1982) [9] and Richardson (1986) [10]; then System Dynamic methods were applied by various researchers to particular areas of interest: police work (Homer, 1993) [11], and Gardiner *et al.* (1987) [12], supply chain management (Towill, 1996) [13], shipbuilding and marine (Cooper, 1980) [14], medical (Homer, 1987) [15]. Other applications of System Dynamics models inlude energy and environment, software engineering and many other diverse areas from organic farming to the fall of the Soviet Union.

One of the broadest areas where System Dynamics found the widest application is Management of Organisations. Many researchers worked on developing market models using System Dynamics Methods, where Coyle was a pioneer with the paper he wrote in 1977 on “Management System Dynamics” (Coyle, 1977) [16]. Later Morecroft (1984) started the topic of System Dynamics application for Strategic Management and design of high-level corporate strategy.

Morecroft [17] reviewed Herbert Simon’s concept of bounded rationality, and, using Forrester’s Market Growth model, he showed how globally ineffective outcomes may arise out of locally effective decisions. In his later works Morecroft further developed the issue of how System Dynamics models can be accessed on their decision rule rationality. Also, Sterman (1989) [18] did a lot of research on how System Dynamics can support decion making in organisations. One of the experiments he performed involved a simple economic system where subjects had to make many managerial decisions. Findings were that the participants would systematically generate expencive oscilliations, ignoring nonlinearities, feedback loops, time delays and accumulations, resulting in poor decision making.

Those findings leaded researchers towards investigating methods of developing computer based management simulators aimed at improving the decisiong making process and organizational learning. In 1988 Morecroft wrote the “System Dynamics and Microworlds for Policymakers” paper on the System Dynamics model building tools available at the time. Two years later Senge, encouraging management to create microworlds, posed the question: “We learn best from our experience, but we never experience the consequences of our most important decisions. How, then, cam we learn?"(Senge, 1990, p.313) [19].

The first Management Flight Simulator game for organizational learning was designed by Kim (1989) [20], and was presented as a case study. Later Sterman and Morecroft (1992) [21] started developing this field, proposing various methods of organizational learning, tools for simulating various mental and formal models and Management Flight Simulators. And in 2003 Communications of the ACM released a special issue called "A Game Experience in Every Application" dedicated to simulation applications and games.

In the very beginning computer based management simulators had to be built on expensive computer workstations and be run in "batch" mode. Statistical packages or programming languages (e.g. Simula, Dynamo, and Dysmap) were used to program variables. Output was textual, numeric or simple histograms (Saunders, 1998) [22]. Since then a major step forward was made with the introduction of new dynamic graphical software.

2.1 Management Simulators Software

Modern System Dynamics modeling software with its graphical user interface and powerful desktop PCs allow their users to quickly sketch causal loop diagrams, registering stocks and flows, feedback patterns, time delays and nonlinearities. No advanced mathematical knowledge is required in order to construct equations, since most of the software uses "friendly algebra". After the model is constructed, the simulation can be run and the results viewed immediately.

Stella/ithink, developed by High Performance Systems, were the first software with full graphical interface for modeling stock and flow diagrams. Other powerful simulation environments were facilitated with Vensim by Ventana Systems, with many features for analyzing model behavior, Microworld Creator from Microworlds Inc. supporting information displays defined by users and Powersim Constructor from Powersim AS, Norway allowing its users easily build models and transform them into simulators. Further AnyLogic a Java based software with multiple simulation methods from XJ Technologies, St.Petersburg, Russian Federation, interacts with users through a web browser and supports many levels of aggregation. Recent software keeps on constantly improving its capabilities by adding new functions, admitting matrix equations and accepting optimization techniques. Still, the software is just a modeling environment making work of a manager or a policy maker more efficient and allowing anyone to participate in the modeling process, but does not replace the thinking activity behind the model construction and development of a Management Flight Simulator.

3 Development for a Management Flight Simulator

The research of the literature performed for the purpose of this paper shows that at present there are no generic frameworks available for the development of a Management Flight Simulator. Different researchers suggested various guidelines on the development of management flight simulators. The various suggestions and guidelines have been reviewed and incorporated in the following framework as shown in Fig. 1. The various stages of framework are explained as follows.

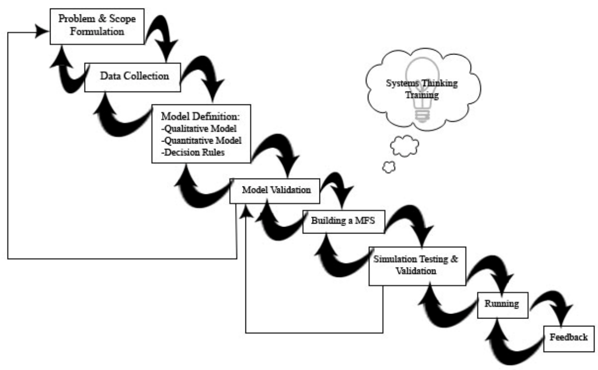

Fig. 1: Proposed Framework for the Development of a Management Flight Simulator

3.1 Formulating the Problem and Scope

The first step is formulation of the problem to be solved and definition of the scope or boundaries of the microworld. Here the questions that the simulation will aim to resolve will be identified. The scope will define how closely the simulator will represent the "real world". This requires careful investigation, to identify what should be a part of the simulation and what can be safely left without oversimplifying the simulation model as Morecroft, (1999) [23] suggested.

3.2 Data Collection

The main purpose of creating a Management Flight Simulator is to enhance the learning process of the person who is to use it. The first step of learning is identifying, documenting and representing the existing knowledge. That is knowledge of the structure of the system under study, patterns of interaction of its components and the decision rules guiding them. The data should be collected through interviews and exchanging information and mental models using quantitative and qualitative System Dynamics methods. All of the main stakeholders and knowledge experts should be involved at this stage. The proper knowledge retrieval and ultimately the construction of this relational framework of the system components is the biggest challenge in the process of development of an effective Management Flight Simulator.

Next, building a Management Flight Simulator would require both qualitative and quantitative (formal) modelling.

3.3 Model Definition

The task of a Management Flight Simulator is to represent the system so that its behaviour can be simulated, predicted, and changed. And that representation is manifested in the system model. It can be defined in three steps: its physical model, the formal model and the decision rules underlying the model.

3.3.1 Qualitative Model – Identifying Stocks and Flows

At this stage the objective is to build a high level aggregate view of the system problem area – a qualitative simulation model. In order to achieve that, we need to construct a causal loop diagram. The structure of the model should accurately reflect the physical side of the system: the stocks like number of roads, road capacity, people, money, information and their flows. Stocks and flows can be identified through interviews, surveys, financial documentation and many other methods involving identification of key stakeholders with different perspectives on the system. Computer software can be used to draw the model. The product of this stage is a graphical causal loop diagram.

3.3.2 Quantitative Model – Model Formulation

The formal models objective is to define how user's actions are processed and what outcomes are produced. Formulation of the model has not undergone any considerable changes over the years. The concrete formulation of a model is carried out using of differential equations, displaying causal relations of the system. And a computer simulation is used to solve the simultaneous differential equations formed by the individual equations (Rego, 1999) [24]. That is the role performed by one of the components of a Management Flight Simulator – a dynamic computational engine. It simulates the elapsing time and defines variables and variables relationships, which can change over time of simulation or at a specified point (Saunders, 1998) [22].

3.3.3 Identifying Decision Rules

While it is relatively easy to define the models components and quantify the model, representing the decision rules of the actors is a much more difficult task (Sterman, 1987) [25]. Here questionnaires, interviews, observations, surveys and other methods can be used.

3.4 Model Validation

The next step after the simulation model is built and quantified is to validate it. The objective of validation is to identify and eliminate errors, and to insure that the model operates as the system it represents, and whether it will answer the questions and cover the scope identified in the first step. This stage involves mainly conceptual validation. And again, the biggest challenge is for the decision models built into a management flight simulator to adequately reflect a rational decision making process. If the model proves to be invalid, then the steps before it have to be repeated, starting from the problem definition and scope.

3.5 Building a Management Flight Simulator

Here the objective is to build a human-computer interaction component of a Management Flight Simulator. Computer software should be used to present the simulation to the intended user giving him/her a variety of components available for manipulation. Also, the decision should be made whether the simulation is intended for a single or multiple users and whether it would be run locally on a PC platform, over the internet or another network.

3.6 Computer Simulation Testing and Validation

Testing can be performed in the form of a direct experiment, as suggested by Sterman (1987) [25] in his paper "Testing Behavioral Simulation Models by Direct Experiment", where subjects play a game and are given the same information set and freedom to make decisions in their own way. At the end the decisions made by the participants are compared to behaviour produced by the decision rules of the game.

Another method of testing is called hypothesis testing of the model parameters. That involves stating how the model should behave when a parameter is changed in a certain way, running the simulation with the changes, and comparing the model behaviour against the hypothesis. A further sensitivity analysis would involve checking whether the model is sensitive enough (and not oversensitive) to the changes in some parameters.

Also, some key performance indicators (KPI) can be set against which the behaviour of the system can be measured.

A series of questions are asked to validate the computer simulation model, which involves conceptual, structural, and behavioural validation. If some serious errors are identified during this stage, the model has to be reconstructed, going back to the first step. That is why it is advisable to perform some testing and validation at each stage of the model construction and to have domain experts available to progressively refine the model.

3.7 Running

The final objective is to perform a what-if analysis testing various policies. The activities at this stage can range from simple change of one variable to complete redesign of a decision rule, a policy scenario or the whole strategy by a decision maker.

3.8 Feedback

There is no learning without feedback, without knowledge of the results of our actions. Thus, a good Management Flight Simulator should analyse the output and provide feedback to the user on why did certain events occur during the simulation, and what could be the meaning of the outcomes.

This framework is very flexible, and allows going up a step at any moment if some changes are required.

4 Conclusions

As a conclusion, it can be claimed that while there are still debates going on about validity of the use of Management Flight Simulators for organizational learning and decision making, they continue to be one of the best methods available for resolving the complexity of large systems. Computer simulations become an indispensable tool when a real-world experiment would be too costly, time consuming, unethical, or unfeasible in any other way, helping us to discover through our own actions how the whole system will react, even if the effects should be seen in a century time.

Organizations may vary in their ability and willingness to adopt and invest in the “flight simulators” development, but with the increasing number of tools and software available for creating a microworld, it is hard to remain skeptical about their use, even for novice computer users. And with employment of such technologies as virtual reality, mobile internet, 3D graphics, artificial intelligence and Web, users experience is becoming more enhanced and closer to the real-world decision-making setting.

Finally, the proposed framework could serve as a generic method for developing realistic management flight simulators. In such computer-based simulators knowledge can be captured, internalized, shared and plausible scenarios may be tested prior to implementation to solve management problems in feedback controlled cybernetic way.

References:

[1] Sterman, J. D. 2000 *Business Dynamics: Systems Thinking and Modelling for a Complex World*. New York: McGraw-Hill.

[2] Sterman, J. D. 2001. *System dynamics modeling: Tools for learning in a complex world*. California management review 43 (1): 8-25

[3] De Geus, A.P. 1992. Modelling to predict or to learn? European J. of Op. Research 59:1-5

[4] Forrester, J. W. 1961. Industrial Dynamics. MITPress; Cambridge, MA: reprinted by Productivity Press (1994) and now available from Pegasus Communications,Waltham, MA, USA

[5] Richardson, G. P. 1991 *Feedback Thought in Social Sciences & System Theory.* Philadelphia, University of Pennsylvania Press. 154-155

[6] Forrester, J. W. 1969. *Urban Dynamics*. Cambridge MA: Productivity Press

[7] Meadows, D. H., D. L. Meadows, J. Randers, & W. W. Behrens III. 1972. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. New York: Universe Books.

[8] Sterman, J. D. 1985. *A Behavioral Model of the Economic Long Wave*. Journal of Economic Behavior and Organization 6 (1): 17-53

[9] Morecroft, J. D. W. 1982. *A Critical Review of Diagramming Tools for Conceptualizing Feedback System Models*. Dynamica 8 (part 1): 20-29.

[10] Richardson, G. P. 1986. *Problems with Causal-Loop Diagrams*. System Dynamics Review 2 (2): 158-170

[11] Homer, J. B. 1993. *A System Dynamics Model of National Cocaine Prevalence*. System Dynamics Review 9 (1): 49-78

[12] Gardiner, L. K. and R. C. Shreckengost. 1987. *A System Dynamics Model for Estimating Heroin Imports into the United States*. System Dynamics Review 3 (1): 8-27.

[13] Towill, D. R. 1996. *Industrial Dynamics Modelling Of Supply Chains*. Logistics Information Managment 9 (4):43-56.

[14] Cooper, K. G. 1980. Naval Ship Production: A Claim Settled and a Framework Built. Interfaces 10 (6): December.

[15] Homer, J. B. 1987. A Diffusion Model with Application to Evolving Medical Technologies. Technological Forecasting and Social Change 31 (3): 197-218.

[16] Coyle, R. G. 1977. Management System Dynamics. New York: John Wiley & Sons.

[17] Morecroft, J. D. W. 1984. Strategy Support Models. Strategic Management Journal 5 (3): 215-229.

[18] Sterman, J. D. 1989. Misperceptions of Feedback in Dynamic Decision Making. Organizational Behavior and Human Decision Processes 43 (3): 301-335.

[19] Senge, P. M. 1990. The Fifth Discipline: The Art and Practice of the Learning Organization. New York: Doubleday Currency. [20] X2. Author, *Title of the Book*, Publishing House, 19XX

[20] Kim, D. 1989. Learning Laboratories: Designing a Reflective Learning Environment. In Computer-Based Management of Complex Systems: International System Dynamics Conference, ed. P. M. Milling & E. O. K. Zahn. Berlin: Springer-Verlag.

[21] Morecroft, J. D. W., & J. D. Sterman, eds. 1992. European Journal of Operational Research: Special Issue: Modelling for Learning, 59 (1). [2] X2. Author, *Title of the Book*, Publishing House, 19XX

[22] Saunders, J. H. 1998 The Management Flight Simulator Information Technology Talk.: http://users.erols.com/jsaunders/papers/mfs.htm

[23] Morecroft, J. 1999. *Visualising and Rehearsing Strategy*. Business Strategy Review 10 (3):17

[24] Rego, J. C. ,1999 After 40 years, has System Dynamics changed? National Research Council of the Argentine Republic. Buenos Argentina

[25] Sterman, J. D. 1987. Expectation Formation in Behavioral Simulation Models. Behavioral Science 32: 190-211