ESD.83 Knowledge Domains in Engineering Systems

System Dynamics: Tackling the World's Complexity

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Introduction

System Dynamics was a field that was created to handle the complexity of real problems. In an interconnected and changing modern world dealing with complex systems can be a daunting task. System Dynamics' basic premise is that the relationships between factors in systems exhibit non-linear behavior. These non-linear relationships are often compounded by several dynamic mechanisms including complexity and information delay. As a result the behavior of a complex dynamic system is inherently difficult to understand and foresee. System Dynamics was a methodology created to cut through the complexity of systems, establish many mathematical relationships between system components and organize the relationships into a whole system model. Simple relationships are built up and added together to get a better picture of how a system behaves. This field of study, while originating as a method to tackle complex world of business management, has found applications in every aspect of life from government policymaking, human biology, and global environmental studies. Many academics, policy makers and business leaders have been won over by the power of System Dynamics as a tool for understanding the world. This short paper describes the history, basis and attractiveness of System Dynamics as a tool for engineering and re-engineering complex systems.

History

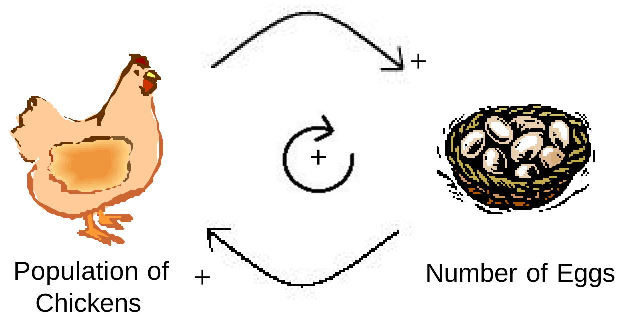
The field of System Dynamics (or SD) was founded in the 1960s at the Massachusetts Institute of Technology by Prof. Jay Forrester. Prof. Forrester had gained wide respect for his work in the field of digital computing following World War II. His development of the Wirlwind computer, the backbone of the SAGE system, was a vital contribution to the United States air defense. Despite his accolades Prof. Forrester became restless with his position in the electrical engineering department. When offered and opportunity to switch to MIT's Sloan School of Management, Prof. Forrester agreed enthusiastically. The Sloan School's affiliation with MIT's technical roots had prompted them to look for more 'scientific' method for business management. Forrester's views on electrical control theory and feedback fit well with the controlling of business. Prof. Forrester translated his knowledge of electrical flows and digital controllers in to a generic mathematical language that could easily be translated to capital flows and inventory control. Forrester summarized his methodology in Business Dynamics published in 1961. This text modeled and explained many modes of behavior viewed in business systems, and was well received in business and academia. Following the release of Business Dynamics SD gained more supporters and Prof. Forrester created a whole department at MIT devoted to the method and its applications. This group lead the way for further SD research into other systems like Urban Dynamics, that describes and models social, labor and population dynamics observed in cities, and World Dynamics, delving into the ambitious pursuit of modeling humanity and its effects on the planet.

Basis for SD

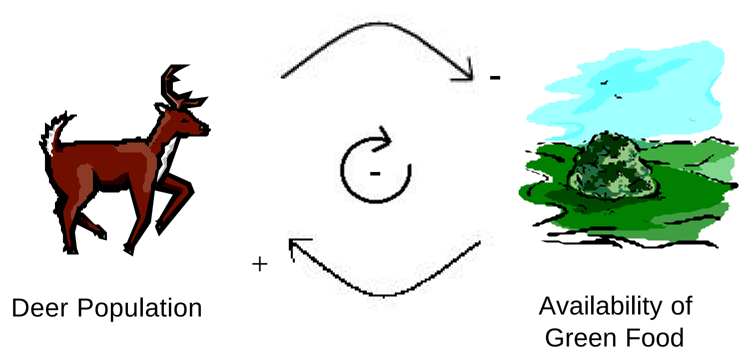
There are two major behavior modes of systems explored by System Dynamics Models:

1) Positive Feedback (exponential growth or decay): Many dynamic systems do not interact in a linear manner. In a dynamic model, positive feedback reinforces

growth (or decay) with a looping structure. A population of chickens (or any population) is a good example. Chicken lay eggs, which hatch into more chickens, that lay more eggs. The chicken population will grow very rapidly in an exponential manner. Many systems exhibit this behavior mode from biological populations to bank interest.



2) Negative Feedback (balancing or equilibrium dynamic): Other dynamic systems try to maintain or balance a system. A good example of this dynamic is a biological population near its carrying capacity. For example, imagine a population of deer is close exhausting a forest's supply of food. Any additional deer will limit food to the others and more will die. If deer migrate away from the forest, more food will be available for the current population and more offspring will be able to survive, increasing the population. This negative feedback enforces and maintains an equilibrium state.



Additional Insights from SD

Understanding the important feed back structure was the basis for much of Forrester's first studies of dynamic systems. However, there are several aspects of real systems that had to be tackled before it was a robust method. When interacting with complex systems, humans normally have to observe or measure the current state of the system. A problem that arises is that no measurement or observation is instantaneous. Data must be collected, analyzed and action plans must be formulated. When interacting with dynamically growing systems this measurement delay can be dangerous. If one is trying to control a rapidly exploding population, by the time you realize that the growth is too much it may be too late. This usually resulted in a boom-bust dynamic that is widely observed in real systems. Modeling delays also allow modelers to understand how seemingly simple systems will have oscillatory behavior.

Complexity also has a major impact on the working of a System Dynamics model. In the final formulation of a large SD model many different feedback loops will be linked together. While each single loop relationship is inherently simple to describe the overall behavior mode of the system may be unforeseeable. The act of decomposing and recomposing the relationships of complexity is another strength of the SD methodology.

Applications of System Dynamics

Non-linear growth, information and observation delay and system complexity are very difficult for the human mind to envision. With Jay Forrester's original work in digital computing many of these complex issues could be address automatically using computers. Combining his two fields of expertise Forrester embarked on a series of modeling studies in several important fields.

In his first SD text, Business Dynamics, Forrester outlines how natural business systems for handling product orders, production and inventory can show oscillatory behavior, even in the presence of stable demand. Forrester also showed how ordering and production scheduling decisions coupled with typical management decision-making delays would actually perpetuate or intensify oscillations in the supply chain.

Forrester expanded the scope of his methodology in his second book, Urban Dynamics. In this text Prof. Forrester and his research group, examined the social and economic dynamics of a large city. In his book, Forrester showed that a rapidly growing urban setting tends to overshoot its housing and employment limits, resulting in urban decay and stagnation. Many viewed this outcome as controversial and his recommendations on how to deal with urban problems were deemed by some as 'Malthusian'. However, others praised this application SD methodology in the environmental area as a call for limiting urban growth and sprawl. This support form environmentalists and sustainability supporters lead to Forrester's grandest model.

World Dynamics by Forrester and Limits to Growth authored by an associate researcher in MIT's SD group, Dennis Meadows, were released in the early 1970s and created much controversy. These two studies culminated work on the most ambitious SD model ever created, a model of the Earth itself. Forrester and Meadows worked in conjunction with the Club of Rome, a group of environmental and industrial leaders that were interested in understanding the rapid growth of human development and its effects on the world. Two years of commissioned research resulted in World 3, a computer simulation of the planet. In the model Meadows tracked the world's population, agricultural land, supply of non-renewable resources, level of industry and level of pollution. The results showed that due to incredible industrial and population growth, humanity would far surpass its limits to feed itself and sustain itself with simple necessities. The model predicted that this would result in a huge population decrease in the 100 years following the study. Even when optimistic parameters for pollution control, recycling of resources and technological development were employed, the world displayed boom-bust behaviors. Again political, academic and industrial leaders attacked the efforts of Forrester and Meadows, as fortunetellers and doomsayers. Others in the environmental field lauded the results as a call for reducing industrial development. There have been many other applications of the methodology since these studies, but Forrester's work is by far the most recognized use of System Dynamics.

Conclusions

The reception of World Dynamics and Limits to Growth was a slight set back the credibility of SD as a methodology, but the method lives on. The main criticism has always been that the method focuses less on accurate data and more on causal relationships. Forrester, himself has acknowledges that this, but contend that over a wide range of possible input data, many systems behave in the same generic ways as those shown in his studies. Exponential growth, balancing at limits, oscillation and boom-bust are pervasive behavior modes of complex systems despite the exact details that are used to form the models. Forrester believed that the real strength of System Dynamics modeling was not the ability to predict the future, but the ability to foresee behavior patterns and make good policy decisions and before systems get out of control.

While the method has its critics, many people have been won over to the cause of SD. System Dynamics is employed in many settings from industry to government to personal decision -making. System Dynamics groups have formed at companies like General Motors (sales and production modeling) and McKinsey and Company (SD consulting). Government agencies have used SD models in many applications from analyzing pollution in cities and economic policy formation. Jay Forrester himself has championed System Dynamics as a teaching tool for grade school instruction. The applicability of the method is wide and its concepts simple enough, that System Dynamics should enjoy a bright future as a way to understand complex systems.

Suggested Reading

Jay Forrester, Industrial Dynamics, MIT Press, 1961

Jay Forrester, Urban Dynamics, MIT Press, 1969

Jay Forrester, World Dynamics, MIT Press, 1972

A. and T. Hughes, eds. Systems, Experts, and Computers, *Chapeter 8 The World in a Machine: Origins and Impacts of Early Computerized Global Systems Model*, by Paul N. Meadows, MIT Press, 2000.

Dennis Meadows et. al., Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind, Potomac Associates, 1972

John D. Sterman, Business Dynamics: Systems Thinking and Modeling for a Complex World, McGraw-Hill, 2000