The Hard Core of the System Dynamics Research Programme

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Introduction

In this research, we attempt to identify the set of basic assumptions underlying the system dynamics research programme. This work is *inspired* by Lakatos' theory of science (Lakatos, Musgrave 1970). Lakatos calls the set of basic assumptions of any programme, the hard core of the programme. The hard core of a programme is the defining characteristic of a programme. According to Lakatos, "the hard core of a programme is rendered unfalsifiable by the methodological decision of it protagonists" (Chalmers, 1982, p. 81). One is unwilling to give up this hard core, even if one meets resistance in the form of empirical counter-evidence, anomalies and scientific arguments. The research to explain the anomalies is sought in the other assumptions, auxiliary hypotheses, initial conditions or what Lakatos calls the protecting belt of the programme.

I think that the research to identify the hard core is very crucial in understanding and evaluating the system dynamics research programme. Many of the criticisms (which will be illustrated later, when discussing the validation issue) of the system dynamics research programme stemmed from a misconception of the hard core of the programme. To understand the origin of such a misconception, we have to recall Kuhn's claim (Kuhn, 1970) that rival theories are "incommensurable" (cannot be measured by the same standards). This stems from the fact that proponents of rival theories will subscribe and adhere to different sets of basic assumptions. Judged by its own set of standards (that is a direct result of its set of basic assumptions) theory A may be judged superior to theory B, while if the standards of theory B are used as premises, the judgment may be reversed. The conclusion of an argument is compelling only if its premises are accepted. Supporters of rival theories will not accept each other's premises and so they will criticize each other from different perspectives.

As Meadows puts it:

> Different modeling worldview, or in Thomas Kuhn terminology, paradigms, cause their practitioners to define different problems, follow different procedures, and use different criteria to evaluate their results. In a very real sense the paradigm biases the way the modeler sees the world, and thus influences the content and shape of his models. "If the only tool you have is a hammer, you tend to treat everything as if it was a nail". …It often leads to sterile arguments across paradigms, each school criticizing the problems, assumptions, and standards of the other from the biased perspectives of its own problems, assumptions, and standards. (Meadows, 1980, p.24)

In the next section, the historical roots of system dynamics will be briefly illustrated. According to Lakatos, the discussion of a specific programme should include a description of the historical context in which it emerged. Then the most important point in this paper, that is the identification of the hard core of system dynamics, will be explained in detail. The last section in this paper is the conclusion.

The Historical Context of System Dynamics

System Dynamics is a computer-aided approach to policy analysis and design. It applies to dynamic problems arising in complex social, managerial, economic, ecological systems, or any dynamic systems characterized by interdependence, mutual interaction, information feedback and circular causality.

System dynamics was originally developed by Jay Forrester at MIT in the 1950s. His classical book "Industrial Dynamics" (Forrester, 1961) is still an important statement of the philosophy and methodology in system dynamics. Initially, system dynamics was named "Industrial Dynamics", as it was targeted to corporate and industrial problems. Only later, the name was changed (evolved) to system dynamics to reflect the breadth and universal nature of the research programme. The name system dynamics can suggest the presence of a link between the system dynamics research programme and other system-based research programmes. In fact, the links are weak and misleading. It will be shown later that the system dynamics research programme is different from the general system theory and cybernetics.

Engineering control theory “servomechanisms” (Ogata, 1997) is the parent research programme of system dynamics. System dynamics took the concepts of engineering control theory and applied it to social, managerial and other domains. In the system dynamics research programme, the methods of management have been extended and improved by methodologies developed in engineering (Forrester, 1961; Richardson, 1981; Richardson, 1991; Richardson 1996). What emanated most strongly to the social science from engineering control were:

- Control or management requires the feedback of information. In particular, the necessary information is the "error signal", which is the difference between the goal and the actual condition of the system.
- Drawing visual diagrams is vital for the conceptualization of a feedback model. Control theory introduced the "block diagram" which was the first formal visual feedback loop diagram ever. As we will see later, system dynamics adopted the stock-and-flow diagram to portray feedback.

Nowadays many managers and consultants use system dynamics as an effective tool to ***redesign*** their organizations' infrastructure. System dynamics is used by managers that want to solve an array of problems, which are resilient to traditional ways of thinking; managers who want to make their organizations more effective, and see their visions come through.

According to Jay Forrester’s philosophical view, corporate executives should be corporate ***designers*** (***engineers***); they should create the policies for their middle managers to be able to make informed decisions. The problems of the corporation will be eliminated by changing the structure, and the policies of the corporation; and the only people in a position to do so are the executives (Forrester, 1961).

The ultimate goal of managers and consultants is to ***design*** a learning organization (Senge, 1994). An organization that is capable of solving current problems, and seizing current opportunities. At the same time, the organization invests in its capacity to obtain and keep the leading edge in the future. The power of the learning organization stems from the ability of its members to enhance and expand their collective awareness and capabilities.

The Hard Core Pyramid

From my point of view (my own reconstruction of the programme based on my experience, education and intuition) the system dynamics' hard core consists of a multi-level pyramid of basic assumptions. Each level sets a foundation on which the upper levels rest. This pyramid consists of six levels. At the first level is the causality assumption. Then comes the assumption that the accumulation process is the fundamental process in nature. Then the basic assumption regarding the "endogenous origin of cause" at the next higher level. Moving up to the fourth level, we find the fluid representation metaphor. Then there is the assumption that human mental inference has a limited capacity. Finally, we reach the assumption that each model by itself is a theory. The folbwing figure illustrates the hard core pyramid of the system dynamics research programme.

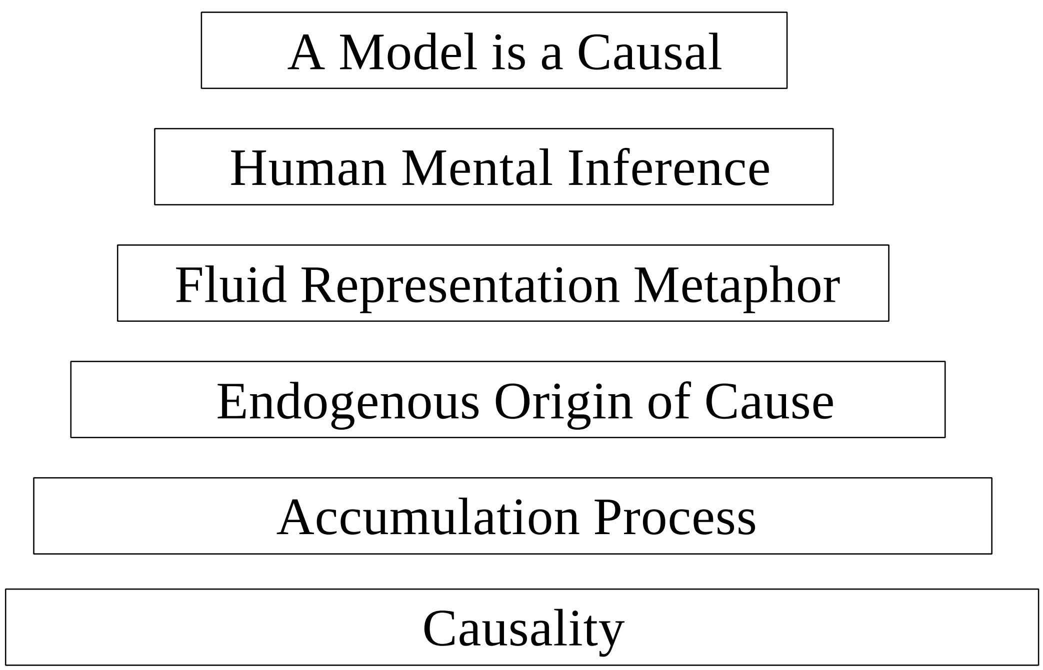

Fig. 1 The hard core pyramid of the system dynamics research programme.

The Causality Assumption

The System dynamics research programme assumes the existence of causal relationships governing the behavior of social systems. There are many questions and doubts about the concept of causality in social systems (Lessnoff, 1974; Elster 1983). From a methodological philosophical perspective, it is impossible to absolutely affirm the presence of any universal causal relationship between two variables. In the System Dynamics programme, it is assumed that concept of causality has a meaning in social science. It is also assumed that we can form closed loops of circular causality (this point will be explained in more details in the endogenous origin of cause assumption).

The following Forrester's quote briefly explains the causality assumption in the system dynamics programme. As Forrester puts it:

> The nature of causality should perhaps be a subheading under philosophy. In system dynamics, causality is implied by the structure of feedback loops. Causality is unidirectional from element to element around a loop. Causality is not ambiguous or reversible. From a system dynamics viewpoint, water flowing from a faucet causes the water level in a glass to rise. And the level of water in the glass can cause a person to shut off the faucet. But I have had people argue that no such sense of causality is justified, that it is just as correct to assert that the water flows from the faucet because the water level in the glass is rising. I do not understand the basis for such a perspective, but confusion does seem to exist regarding causality and its relationship to modeling. An indifference to the importance of causality must underline search in the social sciences for statistical correlations. Statistical correlations can show that one variable "explains" another in the sense that changes in the two accompany each other. But such correlation needs not to imply a direction of causality between the two variables, or even that a direct connection exists. They may both vary as a consequence of a third influence… The social sciences need more emphasis on causality and less on correlation and statistical "explanation". (Forrester, 1980, p. 15)

The Accumulation Process as the Fundamental Process in Nature

Forrester argues that: "Nowhere does Nature differentiate; in real systems, dynamic change arises only from accumulation, that is, integration" (Forrester, 1980, p.15). This is an ontological assumption about reality. In the modeling of real systems, Forrester's focus is on the accumulation (integration) process, rather than on the differentiation process. Yet, the main focus of mathematicians is on the differentiation process. This focus on the differentiation process can be traced back in history to "Isaac Newton", the founder of the differential calculus field. There are two reasons behind the mathematicians’ choice to focus on differentiation. First, the direction of causality is not important to mathematicians. Second, the differentiation process is mathematically simpler than the integration process.

To illustrate this point, I will return to the "water" example given in the previous section (in Forrester’s quote); according to Forrester the water level in a glass rises due to the accumulation process of the water flowing from the faucet. But if we focused (as many mathematicians do) on the flow (the mathematical derivative), that will imply that the flow exists because the level of water is changing. This interpretation can be a valid mathematical statement, but is totally disassociated from the real dynamics of our world.

Forrester believes that many students become confused, when being taught dynamics through the mathematics of differential equations, and that the proper way of understanding dynamics is through the accumulation processes that characterize change.

In reality, the accumulation process is the most fundamental process from which the dynamic behavior of systems originates. Without this process, there will be no dynamics at all; you could not have a dynamic system that does not encompass this process. Yet, for the very reason that it is so fundamental, many authors oversee it when listing the factors that are responsible for the dynamic behavior of complex systems.

The Endogenous Origin of Cause

The endogenous origin of cause assumption is one of the most fundamental concepts in system dynamics. It implies the existence of some other assumptions such as: closed causal boundaries, feedback, nonlinearity, etc.

The Endogenous origin of cause assumption dictates that the root causes of a "solvable problem" associated with a particular system are contained within the internal structure of the system itself. A solvable problem is defined as a problematic behavior that can be adjusted (controlled) by human intervention. As long as the problem of interest is a solvable one (and many of the modern world's serious problems are solvable), then the root causes of the problematic behavior are not a consequence of unavoidable exogenous disturbances, but rather arise from the complex relationships of the structure of the system. It is an inward-looking perspective. It assumes that the essential dynamic behavior of a system results from the inner workings of the system itself. The focus is internal, not external. The endogenous point of view creates a dramatically different problem focus from that of the external view. While the external view places us at the mercy of some unavoidable exogenous events, the internal view inspires us to search for causes (that can be solved) from within our own system. While the external view directs us to identify an uncontrollable source outside the system to blame, the internal view forces us to look for the reason within the system. Thus the system that created the problem can be modified by man, and there is hope to solve the problem. This is the major benefit of the endogenous point of view.

To fully understand the previous paragraph, we need to further understand the relationship between man and system. As Skinner describes it:

> Man himself may be controlled by his environment [system], but it is an environment [system] which is almost wholly of his own making … When a person changes his physical or social environment [system] "intentionally"_ that is, in order to change human behavior, possible including his own _ he plays two roles: one as a controller, as the designer of a controlling culture, and another as the controlled, as the product of the culture. There is nothing inconsistent about this; it follows from the nature of the evolution of a culture, with or without intentional design. (Skinner, 1971, p. 196)

The endogenous assumption necessitates the presence of a closed causal boundary for the system. This closed boundary separates the dynamically significant inner workings of the system from the dynamically insignificant external environment. While, in general system theory a closed system is defined as a materially closed one, in system dynamics a closed system is defined as a causally closed one. In system dynamics, we are focusing on the problem and its causes, rather than on a materially closed "whole" system. A system dynamicist looks for the boundary that encompasses the smallest number of components within which the dynamic behavior of the problem is generated.

Those components are capable by themselves, without exogenous aid, to reproduce the essential characteristics of the problematic behavior. A problem focus acts as a critically important filter that screens out unnecessary details and centers our attention on the significant aspects of the system. The typical case is to have one problem per system dynamics model (where a system dynamics model is a representation of a closed causal system), with the implication that the modeler should exclude everything (from the model) that does not contribute to the problem behavior. The basic idea in modeling is, therefore, to represent a portion of reality, sufficiently large to represent the current problem, yet small enough to exclude everything that is of no significant relevance.

The modeler should also choose the appropriate level of aggregation for the model. The level of aggregation is directly related to the time-horizon of the model. In a long term horizon several smaller components of a system get so thoroughly intertwined, that it makes more sense to aggregate them. The time horizon is in turn dependent on the problematic behavior we want to understand. In system dynamics, we focus on a certain mode of behavior, and deliberately exclude some of the other modes of behavior present. For example a model of long term economic growth may exclude the business cycle fluctuations. The time horizon must be adequate to the mode of behavior we are interested in. The golden rule in aggregation is that the modeler should aggregate to the greatest extent possible, while making the policy variables (the variables the manager can use to solve the problem), the goal variables (the variables describing the problematic behavior), and the causal relationships between them visible in the model (Wils, 1976).

The feedback view of system dynamics can be seen as a consequence of the closed causal boundary and the endogenous assumption. If feedback loops were not present in a closed boundary system, then all causal links would at the end have to be connected to exogenous factors outside the boundary of the system. This will make the behavior of the system a result of those exogenous factors. Since system dynamicists have an internal perspective to problems (as illustrated before), the existence of the feedback loop concept is inevitable.

George Richardson demonstrates in his book titled: "Feedback thought in Social Science and Systems Theory" (Richardson, 1991), that feedback thinking is one of the most penetrating patterns in all social science, and that it is embedded in the very foundations of social science as a fundamental building block. As Richardson puts it "Great social scientists are feedback thinkers; great social theories are feedback thoughts" (Richardson, 1991, p. 2). There is, however, no consensus among social scientists about that. Yet, Richardson has cited outstanding quotes of several famous social thinkers (like Adam Smith, Hegel, Marx, Thomas Malthus, John Dewey, John Staurt Mill, etc.), which illustrate that the feedback concept was largely implicit in their works. For example, the feedback concept is largely implicit in the following quote by Adam Smith, in which he explains the effect of price on production:

> If…..the quantity brought to market should at any time fall short of the effectual demand, some of the component parts of its price must rise above their natural rate. If it is rent, the interest of all other landlords will naturally prompt them to prepare more land for the raising of this commodity; if it is wages or profits, the interest of all other labourers and dealers will soon prompt them to employ more labour and stock in preparing and bringing it to market. The quantity brought thither will be sufficient to supply the effectual demand. All the different parts of its price will soon sink to their natural rate, and whole price to its natural price. (Smith, 1776, p. 57)

In system dynamics, a feedback loop is defined as a closed sequence of causes and effects (circular causality), a closed path of action and information. Also, in system dynamics, a feedback system is defined as a one of an interconnected set of feedback loops.

Feedback thinking can be seen as contrary to open-loop thinking. In a traditional open-loop thinking, after we discover a problem, we design a policy plan to deal with it, and then act on our plan, and that is the end of the problem-solving process. It is usually forgotten that our action will alter the state of the system, cause secondary effects, and thus may generate a new set of problems (for which new policies must be made), or may redefine the problem in a new context. The feedback thinking approach aims at closing such open loops, and completing the link between our actions and the problem that initiated our actions.

Feedback loops are naturally divided into two distinct categories, which are labeled positive and negative. This label is called the polarity of the feedback loop. The concept of polarity gives the feedback loop analytical and explanatory power.

Negative feedback loops are stabilizing loops, which oppose or negate any destabilizing disturbances. Negative feedback loops are also called stabilizing, equilibrating, or self-correcting loops.

In contrast, positive feedback loops are destabilizing loops, which amplify any disturbances. Positive feedback loops are also called destabilizing, self-reinforcing loops. Sometimes they are called vicious circles.

A common feature of a feedback loop is the presence of delay in the flow of information and material throughout the loop. An order of goods does not immediately result in a delivery of goods, crops planted cannot immediately be harvested, the process of averaging sales takes time, new ideas take time to spread, etc.

Delays have the tendency to dramatically change the behavior of a model. According to Jay Forrester, "delays are crucial in creating the dynamic characteristics of information feedback systems" (Forrester, 1961, p. 86). Negative feedback loops can exhibit oscillating behavior if there is a major delay in it. Also, delays usually attenuate the amplification power of a positive feedback loop.

Given the behavior characteristics of the problems addressed by system dynamics, then the endogenous origin of cause assumption forces system dynamicists to include nonlinearities in the structure of their models. To understand the reason, we must first understand the behavior characteristics of the problems that the system dynamics programme attempts to solve. Many problems that the programme addresses are characterized by an unstable, non-linear, self-limiting behavior, or in short, complex behavior. Complex behavior is a typical characteristic of many natural phenomena in the universe. From a pure mathematics point of view, Kovach observed:

> Strange that these nonlinear phenomena that abound so widely in nature should be so interactable. It is almost as if Man is to be denied a complete knowledge of the universe unless he makes a superhuman effort to solve its nonlinearities…..So far, our efforts to scale the nonlinear barrier have consisted of chiseling a few footholds. (Kovach, 1960, pp. 218-225)

Also systems in social sciences, including economics have nonlinear behavior. Jay Forrester in his paper titled: "Nonlinearity in high-order models of social systems" (Forrester, 1987), has clearly demonstrated and has given several examples to this fact.

Complex behavior can never be generated, without exogenous aid (the endogenous origin of cause assumption), by a linear feedback model. A typical control model (recall that the control theory is the parent programme of system dynamics) will be a linear feedback one. That is because most engineering applications do not exhibit such kind of complex behavior. Yet, Jay Forrester had to step out of the linear world into the nonlinear universe to be able to address the problems in social science exhibiting complex behavior.

In such kinds of complex behavior, no static view of the feedback loops of the model is therefore sufficient. It is necessary for the feedback loops to change endogenously their relative strength of influence as conditions (states) change to generate such complex behavior. In system dynamics terminology, we call this the ability of the model to endogenously shift its dominant loops. Dominant loops are loops that are primarily responsible for the behavior of the model over an interval of time. Loop dominance usually shifts among a number of loops in the course of time. For example, the self-limiting behavior (the so-called S-shaped behavior) can be generated by two coupled feedback loops. One loop is positive and the other one is negative. In the beginning the positive feedback loop is dominant and this generates the exponential growth behavior and then, as the model changes its state, the negative feedback loop dominates and the saturation behavior results.

The endogenous shift in loop dominance takes place as a consequence of nonlinearities in the equations defining the model's structure. If these equations were linear, no such shift in loop dominance would occur, and only one fixed set of loops will continuously dominate the model. In system dynamics, we expect models to change their dominant structure over time. Consequently, we focus on non-linear models. As Forrester puts it: “Indeed, from a feedback loop perspective, this ability to shift loop dominance is the fundamental reason for advocating nonlinear models of social system behavior” (Forrester, 1987, p. 105).

The concept of shifting loop dominance and the presence of nonlinearities are vital supporting pillars for the feedback concept. As George Richardson puts it:

> In fact, without the concept of shifting loop dominance, without nonlinearities in formal models of complex systems, the feedback concept is justifiably perceived to be a weak tool incapable of capturing important dynamics in real systems. (Richardson, 1996, pp. 149-150)

That is the reason for the emphasis system dynamicists put on the concept of the feedback loop dominance. As John Sterman puts it:

> The concept of feedback-loop dominance is central to the system dynamics paradigm. In complex systems _high order, multi-loop nonlinear feedback systems_ behavior over time depends on which of the many feedback processes in the system dominates. At any moment in the evolution of the system, some feedback loops will be highly influential and other will be inactive. Because of nonlinearities, loop dominance often shifts as the behavior unfolds. As the system enters new regions of state space, latent loops that have had no role in the behavior may suddenly become active, causing qualitative changes in the mode of behavior. Endogenous shifts in loop dominance are responsible for shifts from, for example, exponential growth to decline or from stability to instability_ they are responsible for bifurcations. These nonlinear interactions lie at the heart of many important behaviors observed in models. Understanding the nature of loop dominance and the factors that cause it to shift endogenously is critical to the design of robust policy. (Richardson, 1984, p.67)

Structural changes are considered to be of significance and are handled quite differently in cybernetics and in system dynamics programmes. In traditional cybernetics, structural changes are captured linguistically and sometimes diagrammatically, for example by redrawing the system structure. In the more quantitative programme, the system dynamics programme, structural changes are represented by endogenous shifts in loop dominance, which are capable of changing the active structure over time (Forrester, 1987).

Finally, I would like to point out the principle outstanding problem in the system dynamics programme. In the system dynamics programme, it is assumed that there is a closed feedback loop (a hidden meta-loop) between structure and behavior (Davidsen, 1991). Shift in loop dominance is a result of the dynamic behavior of the model itself. These shifts in loop dominance change the active structure of the model. As the active structure changes, so does the dynamic behavior of the model, which in turn further shifts the dominance of the loops, and so on. Understanding the mechanisms of this meta-loop is the principle outstanding problem in the system dynamics programme. The goal is to understand the mechanisms of this hidden meta-loop in the model first (i.e. assuming that the model is our virtual world), then to reflect our understanding of the model on the real system. System dynamics has a great potential in describing the complexity of the real world (something that many modeling programmes lacks), yet currently the explanatory power of system dynamics is not adequate. The major challenge, in future, for the system dynamics programme, is to develop new concepts and tools that can enhance the explanatory power of the programme through innovative ways of *"tracing"* in depth the mechanisms of this hidden meta-loop; otherwise the programme is under the threat of reaching a “crisis” state.

The Fluid Representation Metaphor

From a pure mathematical point of view, the basic structure of a formal system dynamics computer simulation model is a system of coupled, nonlinear first-order integral equations. Higher-order equations can be constructed by cascading several first-order ones. A system that can be represented this way is called a state-determined system in the engineering literature.

Jay Forrester has invented the fluid representation metaphor to hide the mathematical complexity of Integration. Recall that (as discussed before) the integration (accumulation) process is the most fundamental process from which the dynamic behavior of systems originates. System dynamicists take the simplifying view that feedback systems involve continuous, fluid-like processes. The idea of Jay Forrester was to describe in nonmathematical terms the engineer's notions of a state-determined system (Forrester, 1961).

Jay Forrester has used the term stock as analogous to the term state variable in the engineering field. The level of the stock is analogous to the value of the state variable. The term level is intended to invoke the image of the level of a liquid accumulating in a tub. The variables increasing and decreasing a stock are called flows. The speed of a flow is called the rate. In engineering terminology, rates are the components of the derivatives of the variable states. Jay Forrester has also invented the stock-and-flow feedback diagram to facilitate the conceptualizing of the model's structure and the communicating of the model-based insights (Forrester, 1961). Flow diagrams portray flows and stocks as valves and tubs, thus further emphasizing the analogy between the integration process and the fluid accumulation process. The Flow diagram enables the modeler to visually distinguish integral equations from algebraic equations. Integral equations are represented as conservative fluid flows, while algebraic equations are represented as non-conservative information links. The distinction between information and conserved flows is a crucial insight stemming from our new information era.

I would like to note that in system dynamics, a stock can represent measurable, as well as non-measurable (soft) variables. Some soft non-measurable variables can be very crucial to understand and solve our problems. Examples of soft variables are moral, love, happiness, etc. The usual practice in system dynamics is to numerically scale those soft variables. Currently, there is research to use fuzzy logic to represent soft variables (De Kok, 1997).

The clarifying power of levels and flows increases when we take a continuous view of a system. Although a discrete view, focusing on specific events and decisions, is entirely compatible with the endogenous assumption, Jay Forrester, by choice, adopted a continuous point of view, despite the fact that a continuous view of a system is usually hard to achieve. One usually sees discrete events and makes discrete decisions. Jay Forrester in his seminal book "Industrial Dynamics" argued that a continuous view helps us to focus on the most important aspects of the systems, and that the dynamics of a continuous flow model are easier to understand. As Forrester puts it:

> A continuous flow model helps to concentrate attention on the central framework of the system. This framework is more orderly and unchanging than usually expected. Diversion of attention toward separate isolated events tends to obscure the central structure of the system that we are trying to define. (Forrester, 1961, p. 65)

According to Jay Forrester, in the dynamic thinking process one should focus on patterns over time rather than on discrete events, one should group individual events to form a pattern of behavior. To be consistent with this continuous point of view, Forrester chose to view decision making as a continuous process.

> [Decision-making] is a conversion mechanism for changing continuously varying flows of information into control signals that determine rates of flow in the system. The decision point is continually yielding to the pressures of the environment. (Forrester, 1961, p. 96)

Forrester's focus was on policy rather than discrete decisions.

> Policy is a formal statement giving the relationship between information sources and resulting decision flows. It is what has often been referred to in the literature as a decision rule. In physical systems, particular in the field of servomechanisms, the corresponding term is "transfer function". (Forrester, 1961, pp. 96-97)

Forrester saw both an overt and an implicit policy structure in an organization. Overt decisions are the conscious decisions people make, while implicit decisions are unavoidable results of the physics of the system (Forrester, 1961, pp. 102-103).

The net result of Forrester's view of the decision process was the connection of the feedback concept with the decision making process at a certain level of aggregation determined by the emphasis on continuity.

After designing the fluid representation metaphor, Jay Forrester elevated it from a representation schema to the level of principles of a feedback system. He presented several principles to indicate the way feedback-loops must be captured. Nowadays, the system dynamics modeling packages enforce system dynamicists to adhere to Forrester’s principles. Forrester’s principles distinguished feedback loops as portrayed in system dynamics models from other types of feedback loops. Some examples of Forrester's principles are listed below. The reader can refer to Jay Forrester book "Principles of Systems" (Forrester, 1968) for a more complete list of principles.

1) A feedback loop consists of two distinctly different types of variables: the levels (states) and the rates (decisions or actions). Except for constants, these two are sufficient to represent a feedback loop. Both are necessary.
2) Levels integrate (or accumulate) the results of actions in a system.
3) Levels are changed only by rates.
4) Levels and rates are not distinguished by units of measure. The identification must recognize the difference between a variable created by integration and one that is a policy statement in the system.
5) Rates are not instantaneously measurable. No rate can, in principle control another rate without an intervening level variable.
6) Level variables and rate variables in a feedback loop must alternate.
7) Levels (state variables) completely describe the system condition (state)
8) Levels exist in conservative subsystems; they can be changed only by moving the contents between levels (or to or from a source or a sink).
9) Information is not a conservative flow; information is not depleted by its use.
10) Decisions (rates) are based only on available information.

The Limited Capacity of Human Mental Inference

This assumption states that unassisted human-beings cannot infer the behavior of complex dynamic models. In a complex model, feedback loops are constantly interacting, gaining, or losing strength relative to each other (shift in loop dominance), and thus creating a behavior that cannot be inferred by the unaided human mind.

Man cannot assimilate and process all the information required to mentally generate the behavior of a complex dynamic model. Also, man can at most look a few steps ahead in future.

This assumption claims that computers must be used to simulate the behavior of such models. System dynamics allows the application of logic to reveal essentially tautological, but in practical terms, hidden results.

As Jay Forrester puts it

> The fourth foundation for industrial dynamics progress is the electronic digital computer that became generally available between 1955 and 1960. Without, the vast amount of work to obtain specific solutions to the characteristics of complex system would be prohibitively expensive ... The appearance of high-speed electronic digital computers has removed the practical computational barrier. (Forrester, 1961, p.18)

The feedback structures of real problems are often so complex so that the behavior they generate over time can be only traced by simulation. The Latin verb simulate means to imitate or mimic. The idea behind simulation is to mimic the real system so that the behavior can be identified.

One can argue that this assumption is just a technical issue. Yet, in my point of view, this assumption points to an important philosophical difference between system dynamics and the general "System Thinking" programme. General system thinkers use causal loop diagrams and generic structures to illustrate common behavior, but they imply that a system's behavior can be inferred from the feedback loops alone. Or they advocate "fitting" a problem to a generic structure and then suggest a behavior that allegedly will originate from the generic structure. In the same spirit, they suggest how the structure can be modified to alleviate the problem. For example, some system thinkers in cybernetics (e.g., Beer, 1981; Beer, 1995) map the parts of the company to the parts of the body and then giving a generic "answer" accordingly. General system thinkers do not necessarily use computer-based simulation models to relate structure to behavior. The System dynamics programme, on the other hand, takes the information about a system's structure that normally remains hidden in mental models and formalizes it into a computer model. The behavior generated by that particular structure is only revealed when the model is made subject to simulation. Model simulation is a prerequisite in the system dynamics research programme.

System Dynamics Models as Causal Theories

Each model by itself is a theory. A model is a concatenation of causal laws offering a plausible representation of a real system and hence an explanation of a certain behavior.

The general goal of a system dynamics model is understanding. The aim is to understand how the internal structure of the system generates the problematic behavior.

The dynamic hypothesis in a system dynamics based theory is a statement describing the smallest system structure that is postulated to endogenously generate the problematic behavior. The dynamic hypothesis is usually given as a descriptive diagram of interconnected closed causal loops. To test the dynamic hypothesis, a formal quantitative system dynamics model is built (based on the dynamic hypothesis) and then through comparing the model with reality, we can validate the model and hence the dynamic hypothesis.

After understanding the cause of the problem, the modeler should try to understand what policies could improve the problematic behavior and for what reasons. The final goal of a modeling study is the application of model insights; the aim is to help some people manage some activities better in future. Policies could be formal or informal. Informal policies are consequences of habits, intuition, personal interests, and social pressures and power within the organization. On the other hand, a formal policy is explicit and enjoys a formal awareness of the reasons for action.

In system dynamics, it is not enough to know that a particular policy improves model behavior. The critical question is why. No manager or executive will be convinced to implement a policy in the real world just because it made the model behave better. The manager must have a clear understanding of the reason of the problem, and a clear understanding of the reason that makes a particular policy solves the problem. What managers really need is a change in their mental model. This is the essence of building a system dynamics model: that is to elicit the mental model of a manager and to built a formal model based on this model; the computer simulations can consequently be used in testing this formal model (which can never be done on the manager's mental model as we explained before), for the purpose of detecting contradictions and flaws in the manager's mental model, hence correcting them and discovering the real reason of the problem. Then we can experiment with the formal model (using computer simulations) to design policies that solve the problem.

Management flight simulators and interactive learning environments are largely used to *communicate* policy insights. An interactive learning environment is not the same as a management flight simulator. A management flight simulator can be considered a part of an interactive learning environment. While a management flight simulators engages the user in simple interactions with a simulation, an interactive learning environment is firmly established on instructional design theory, which is based on the cognitive learning theory (Davidsen & Spector 1997). Interactive learning environments are transparent boxes that demonstrate to the learners the relationships between key system variables and the most influential delays and feedback loops in the system. It is important for the learners to acquire an understanding of the structure of the system, if the learning goal is to understand the behavior of the system.

Archetypes are also used to *summarize* and *communicate* generic insights about complex system dynamics models. The word "archetype" comes from the Greek word "archetypoes" meaning the first of its kind. System archetypes were originally developed at Innovation Associates in the mid-1980s. The aim of archetypes is to help catalogue the most commonly seen behaviors as being generated by simple generic structures. As Peter Senge puts it:

> Archetypes are accessible tools with which managers can quickly construct credible and consistent hypotheses about the governing forces of their systems. Archetypes are natural vehicle for clarifying and testing mental models about those systems. They are powerful tools for coping with the astonishing numbers of details that frequently overwhelm beginning system thinkers. As you work with archetypes, and they become second nature, they will become part of your diagnostic repertoire. You will be able to talk about systematic issues at a surprisingly sophisticated level. (Senge, 1994, p. 121)

Not all system dynamicists have exactly the same set of archetypes in their mind, but there is a common set of archetypes shared among most system dynamicists. This common set evolves and changes as the system dynamics programme matures. According to Peter Senge, “some archetypes, including ‘Limits To Growth’ and

‘Shifting the Burden’, where translations of ‘generic structures’ _ mechanisms which Jay Forrester and other systems thinking pioneers had described in the 1960s and 1970s” (Senge, 1994, p.121).

After presenting and communicating the model insights (which will hopefully change the mental models of the managers), comes the hardest part in any system dynamics project, that is the implementation of the proposed policy in the real system. It is really the most crucial and difficult phase. Policy studies are usually faced with many uncertainties in the real environment, and many implementation obstacles in the real system. Therefore the modeler has to identify the extent to which the policy outcomes are sensitive to changes in the uncertain factors in the environment (i.e. the degree of robustness of the policy), and has to identify the extent to which the policy recommendations are implementable.

Finally, I would like to point out here a controversial issue in the various modeling programmes for many years; an issue that has witnessed a heated debate over the last 40 years. This issue is model *"validation"*. From this long debate, one can summarize the various critiques of the system dynamics validation methodology, in one common general critique: that system dynamics does not employ objective, quantitative model validation tests (Barlas, 1989; Barlas, 1990; Barlas, 1996; Bell & Senge, 1980; Forrester & Senge, 1980; Sterman, 1984).

I will base my defense of the system dynamics validation methodology on three philosophical arguments. The first argument is that rival programmes are "incommensurable" (see the introduction section). The second argument is that the system dynamics programme adopts a sophisticated falsificationism philosophy, rather than a naive falsificationism one. The third argument is that a system dynamicist does not assume that his model is the only objective representation of a real system, but rather assumes that his model is one of many possible ways of describing the real system. I will explain each argument in details in the following paragraphs. Yet, I would like to point out here, that in my opinion (I will give reasons below for that opinion) the system dynamics validation methodology is *"bolder"* than the validation methodologies of other rival modeling programmes. The word *"bolder"* here means that the number of "potential falsifiers" of a system dynamics model are more than the number of "potential falsifiers" of other types of models.

To understand the first argument (rival programmes are incommensurable), we have to recall Kuhn's claim that in some cases the disagreement between scientists as to which of a pair of theories to prefer arises from disagreements about the purpose of the two theories, or in other words the relative importance of various values by which one can evaluate the two theories. As Kuhn describes it:

> What it should suggest, however, is that such reasons {accuracy, simplicity, fruitfulness and the like} function as values and they can thus be differently applied, individually and collectively, by men who concur in honouring them. If two men disagree, for example, about the relative fruitfulness of their theories, or if they agree about that but disagree about the relative importance of fruitfulness and, say, scope in reaching a choice, neither can be convicted for a mistake. Nor is either being unscientific. (Kuhn, 1970, pp. 199-200)

This is the case in the different modeling schools; the disagreement is about the purpose of various types of models. To understand the origin of this disagreement we have to distinguish between two basic types of models: pure correlation models and pure causal models (Meadows, 1980). Pure correlation models are simply constructed from observed statistical correlations among various elements of a real system. A pure correlation model is an empirical data-driven model; one cannot compare or (validate) any relationship in the model against any known theory that explains this relationship. Moreover, correlation models usually use dummy variables that do not exist in reality. The pure correlation model is said to be valid if the model output behavior matches the observed data to a certain degree of numerical (*quantitative*) accuracy. This is primarily because the only purpose of a pure correlation model is to predict the short-term future. Normally nobody expects the pure correlation model to explain the causes of the behavior (short-term or long-term). On the other hand, pure causal models (much like system dynamics models) are much like a scientific theory in the sense that they attempt to explain how the real world really works (a realism philosophy). That is the primary purpose of a system dynamics model. Thus it makes sense that the essence of model validity (in system dynamics) lies always in structural validity. That is, "the right behavior for the right reasons", not the "right behavior for the wrong reasons" (like in pure correlation models where you introduce imaginary dummy variables to get the right behavior).

Now, I will explain why the validation methodology of causal models is *"bolder"* than that of correlation models. As a system dynamics model is a concatenation of many causal relationships, then, if a single causal relationship is rejected (because it contradicts reality), then the whole model must be rejected. Also any variable in the model must have a real world counterpart. Thus the potential falsifiers of a system dynamics model are much more than those of a pure correlation model. In system dynamics, the term “structure validation” is used to describe the process of corroborating the model through checking those potential falsifiers. Moreover the output behavior of a system dynamics model has to *qualitatively* match the observed data. In system dynamics, the term “behavior validation” is used to describe this process. To end this argument, I would like to point out that system dynamicists rely on a broader range of information sources for creating, and validating the model. While pure correlation models are based only on numerical information, system dynamics models are based on mental (knowledge stored mentally in people's heads), written (information stored descriptively in writings) and numerical (numerical databases) information. As Forrester suggests: "The amount of available information declines, perhaps by a factor of a million, in going from mental to written information and again by another factor of a million in going from written to numerical information" (Forrester, 1980, p. 555).

The second argument was that system dynamics adopts a sophisticated falsificationism philosophy rather than a naive one. According to the naive falsificationism philosophy, all system dynamics models (created till now) are false models, and all of them must be rejected. There is no such thing as a "perfect" system dynamics model. Perfection here means that the model behavior is an exact duplicate (point by point) of the real system behavior, and that there is no discrepancy between the output behavior of the model and the system real behavior. In fact, understanding a "perfect" model would be as difficult as understanding the real world. Modeling, by virtue of its name, however, is a simplification process applied to real world phenomena in order to understand the important aspects of world. Any system dynamics model has some simplifying assumptions that lead us to ignore some minor effects. Also many system dynamics models deliberately exclude some modes of behavior and focus only on the problematic mode of behavior (as we mentioned before). According to the sophisticated falsificationism point of view, the discrepancy between the output behavior of the model and the historical data can be traced back to those simplifying assumptions, and the model can be accepted as long as the model can be corroborated (structurally and behaviorally validated), and as long as the model can predict novel phenomena.

The third argument is that a system dynamicist does not assume that his model is the only objective representation of a real system, but rather assumes that his model is one of many possible ways of describing the real system. A system dynamics model has some subjective nature, in the sense that it is influenced (biased) by the modeler's background knowledge, his ideology, etc. This does not mean that system dynamics models are not built through direct observations of the real world, (it neither means that models are not validated through direct observations of the real world), but rather means that "neutral observations" are something impossible in this world. The fact that system dynamics rely heavily on mental information (rather than just numerical information as many other programmes) makes system dynamics models more susceptible to "subjective observations". Yet, as we described before, the essence of system dynamics modeling is to map the subjective mental model of the manager (which must be subjective, otherwise he should not be a manager) to a formal computer model, that can be made subject to experimentation through various simulations.

Conclusion

In this paper, we identified the hard core of the system dynamics program, and illustrated its coherence; through presenting the hard core as a multi-level pyramid of basic assumptions, where each level in this pyramid sets a foundation on which the upper levels rest. We then discussed each assumption in details.

We discussed the most controversial issue in the programme, which is the validation issue. We found that it is directly related to the incommensurablility concept (as defined by kuhn's theory of science). One must understand the basic assumptions and values of the system dynamics programme to adequately evaluate a system dynamics based theory.

We also identified the principle outstanding problem in the system dynamics programme, that is to fully understand the mechanisms of the hidden meta-loop between structure and behavior.

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