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Modeling for Insights

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Abstract

System Dynamics is a computer-aided approach to evaluating the interrelationships of different components and activities within complex systems. The methodology is used in many fields including global environmental analysis of the world system[1,2], global and regional sustainable development issues[3], environmental management[4], water resources planning and management[5], and environmental and ecological modeling[6]. The real power of System Dynamic modeling is gaining insights into total system behavior as time, and system parameters are adjusted and the effects are visualized in real time. System Dynamic models allow decision makers and stakeholders to explore long-term behavior and performance of complex systems, especially in the context of dynamic processes and changing scenarios without having to wait decades to obtain field data or risk failure if a poor management or design approach is used.

The Idaho National Laboratory recently has been developing a System Dynamic model of the US Commercial Nuclear Fuel Cycle. The model is intended to be used to identify and understand interactions throughout the entire nuclear fuel cycle and suggest sustainable development strategies. This paper describes the basic framework of System Dynamics and then shows how to apply the concepts on a current model and presents examples of useful insights gained from the model.

System Dynamics

System Dynamics originated from the work of Jay W. Forrester at the MIT Sloan School of Management[7]. Coyle defines System Dynamics as follows: "System Dynamics is a method of analyzing problems in which time is an important factor, and which involve the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world."[8]

Often, when first exposed to either Systems Engineering or System Dynamics, one is naturally prompted to ask: What is a *system*? A system is usually defined as the combination of two or more elements that are interconnected for some purpose. A bicycle, a car, and a bus are all systems for transportation. And at a larger scale, the collection of roads and vehicles represents another transportation system. At a still larger scale, this system could include the socio-economic and environmental impacts of various transportation systems and their management. As Andrew Ford points out, "The distinguishing feature of a system is the impression that the whole is more than the sum of its parts."[5]

System Dynamics is profoundly capable of addressing two fundamental questions: What system structure gives rise to a given behavior? How can that system be modified so as to produce a different behavior? To facilitate the understanding of dynamic systems, System Dynamics relies heavily on computer-based modeling, simulation and analysis. Modeling tools typically support the development of multi-attribute, multi-scenario simulations that provide us with insight about the dynamic, developing behavior of complex systems when exposed to a myriad of internal or external, known or predicted perturbations. In this way, System Dynamics represents an analytic path that, when carefully followed, allows us to *forecast*, at least in a comparative sense, the future.

In order to understand more clearly how System Dynamics is applied, it is necessary to understand the concepts of *stocks and flows*, and *causal loop* diagramming. System Dynamics often builds systems using the analogies found in grammar. Stocks, for example, act as nouns in the *sentences* that describe the system; flows act as verbs. Causal loop diagrams are a technique to portray the information feedback at work in a system. The word *causal* refers to cause and effect relationships, which are inherent in complex system element interdependencies. The word *loop* refers to a closed chain of cause and effect.

Complex systems are an interlocking structure of feedback loops. A "feedback loop" is defined as a structure where a decision causes an action, which changes the state of a system, which leads to future decisions. All complex systems involve feedback loops. Urban hydrology is a complex system and it involves many feedback loops. The difficulty in designing the structure is to seek out the feedback loops in a complex system and to properly define the interactions with the whole structure. Figure 1 is an example of one simple feedback loop in an urban dynamic model. In this loop as population increases it causes an increase in water demand that decreases water surplus which decreases attractiveness to the area which affects increases to population. This is a very simple feedback loop.

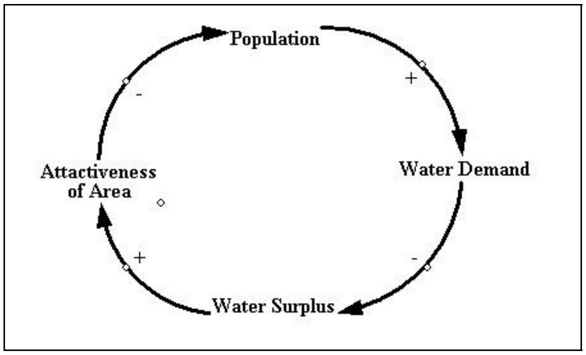

Figure 1: Diagram of a simple feedback loop associated with urban hydrology.

The next step is to include secondary feedback loops that interact with the main loop. Figure 2 is an example of a more complex feedback loop structure.

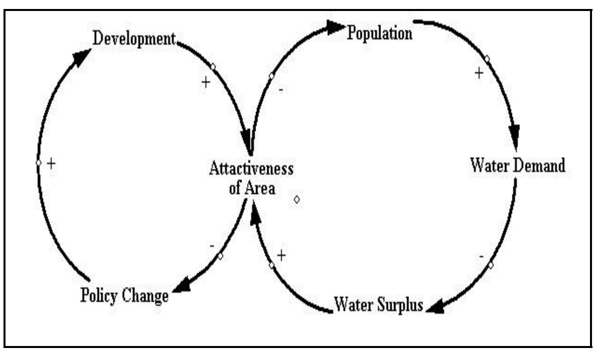

Figure 2: Diagram of a second order feedback loop associated with urban hydrology.

Interplay between these loops is what causes the system to behave in a particular manner. As the system changes, dominance may change from one loop may to another loop.

Dominance means that one loop is controlling the behavior more than any other. A complex system has many such intersecting feedback loops.

An urban area's attractiveness is based upon many factors including housing, schools, safety, employment, tax rates, weather and crowding. If an urban area has a high level of attractiveness then migration into the area is to be expected. As migration occurs then several factors that influence attractiveness will cause the attractiveness of the area to once again move to equilibrium of other urban areas. An urban area cannot expect to remain abnormally high in attractiveness in the long run. Something will change to cause the system to adjust.

The (+) and (-) labeling implies either a positive or negative feedback loop, respectively. Positive feedback means that an increase in the first variable causes a positive increase in the recipient variable. Negative feedback means that a positive increase in the feed variable causes an opposite effect on the recipient variable.

Unfortunately, System Dynamics models are often misrepresented as predictive models, when in fact they are primarily designed to foster general understanding. General understanding of the dynamic behavior of complex systems is important, because without this understanding it is difficult to avoid surprise, identify and characterize options, prioritize management strategies, or—importantly—determine how best to achieve and even how to best define a set of customer requirements in the face of rapidly changing socio-economic and environmental conditions.

Simulation

The real power of simulation models lies in learning insights into total system behavior as time, key parameters, and different scenarios are considered. This is more valuable (and more credible) than attempting to make design and management decisions on the basis of single-parameter point estimates, or even on sensitivity analyses using models that assume that the system is static. System dynamic models allow designers and stakeholders to explore long-term behavior and performance, especially in the context of dynamic processes and changing scenarios. When comparing different management/design scenarios did the system perform better or worse over the long term?

Indeed, the reason the user input is described as a “cockpit” is that such a model allows the designer/stakeholder to simulate piloting a system over time. Instead of simulating an aircraft flight, we simulate a socio-economic system with as many of its dynamic characteristics as possible. After repeated simulations, a student pilot gains deeper understanding of how the aircraft systems will respond to various perturbations (none of which will exactly match a real flight) – without the expense and risk of gaining such experience solely in real flights. Similarly, a manager learns how his system may respond to time and various perturbations – without having to wait decades to obtain field data or risk failure if a poor management or design approach is used.

Example

VISION is the Advanced Fuel Cycle Initiative's (AFCI) nuclear fuel cycle systems code.[9] VISION tracks the isotopic mass-flows of uranium, plutonium, minor actinides, and fission products throughout the entire fuel cycle.

Figure 3 shows a schematic of the VISION model, which is organized into a series of modules that include all of the major facilities and processes involved in the fuel cycle, starting with uranium mining and ending with waste management and disposal. The arrows in the diagram indicate the mass flow of the fuel; VISION provides an isotopic mass balance of fuel and an element mass balance of fuel by-products, such as cladding. Not shown, but included in each module, are the information, decision rules, and requirement flows among the modules that form the logic for the mass flow in VISION.

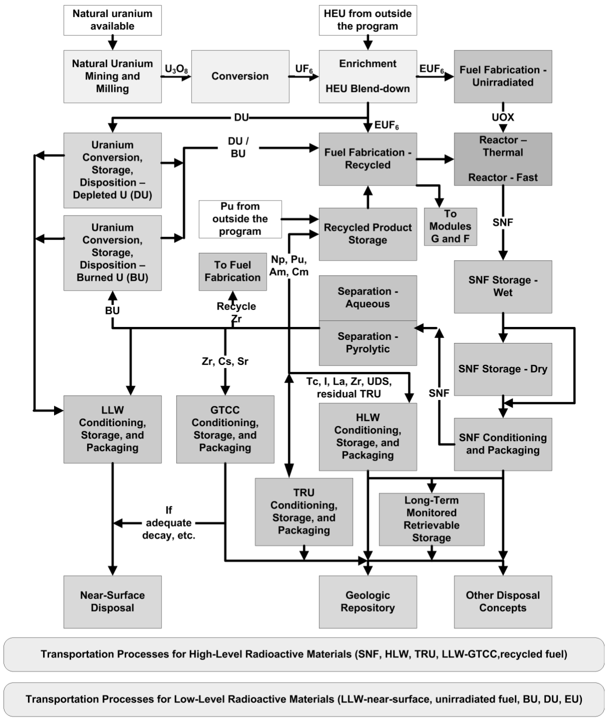

Figure 3: Schematic of the VISION Model flow control.

The model is designed to compare options for processes such as reactor deployment, fuel separation, fuel fabrication and waste disposition within the fuel cycle. VISION enables the user to look at timing issues, mass flow, economics and other factors for the overall system as well as individual processes within the system.

The current nuclear fuel cycle is a once through strategy (open fuel cycle – use fuel once and then dispose of it). One of the options being considered for closing the fuel cycle is using fast reactors to recycle used fuel from thermal reactors. Currently, all nuclear power plants in the US are thermal reactors. If a closed fuel cycle is implemented using fast reactors, a new type of reactor will be added to the system. VISION is set up so that new reactors, thermal or fast, can only be added when there is demand for additional power and fuel is available for the reactor. Given these assumptions, what percentage of the total power will be supplied by fast reactors by 2100 and is this percentage affected by the overall growth rate of the power demand? We assumed that higher growth rates would provide more opportunity for fast reactors to enter the system; we expected that the percentage of fast reactors would increase with growth rate. However, VISION showed us that we neglected to fully consider the time lags inherent in the system. As is shown in figure 4, the percent of total power supplied by fast reactors (by 2100) decreases as the growth rate increases. Figure 4 also shows that the dynamic or effective equilibrium also decreases as the growth rate increases. This behavior is the result of two factors: the time required for recycling fuel and the decision process for adding fast reactors. Fuel exiting a thermal reactor requires approximately 7 years of storage and processing before it can be reused in a fast reactor, fuel from fast reactors can be reused more quickly, but still requires about 3 years of storage and processing. This limits how quickly fuel is available for fast reactors. The fast reactors under consideration are converter fast reactors, meaning they are net consumers of transuranics, and require additional used fuel each refueling to continue operation. Fast reactors are added when additional reactors are needed to meet the power demand and sufficient used fuel is available. If no power demand exists, no reactors are built. If no fuel is available, then a thermal reactor is built. When growth is slow the rate at which new reactors are requested is about the same as the rate of processing used fuel. As the growth rate increases, the rate at which new reactors are requested is greater than the rate of processing used fuel. This means that proportionally fewer fast reactors are built.

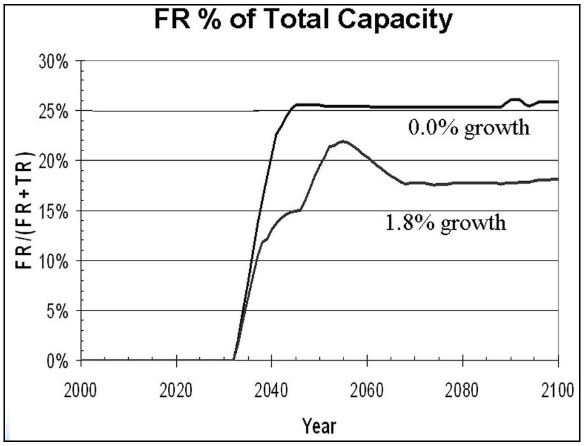

Figure 4: Percent of total power supplied by fast reactors as a function of power growth rate.

Conclusion

We learn through many different activities, watching, reading and practicing. We understand best when we are actively involved with the activities. There is an old adage, "Tell me and I'll forget; show me and I might remember; involve me and I will understand". This holds true in business also. We learn from trial and error. But learning only works so long as the feedback from our actions is rapid and unambiguous.[10] However, most business decisions are far removed in time and distance from the consequences and far from unambiguous, this limits the learning process. Senge argues that important decisions often land in a distant part of the system or far into the future. He explains that flight simulators enable managers and management teams to improve the prospects for "learning through doing" when they "compress time and space."

For high-stakes strategy analysis, a System Dynamics model, as a result of upfront scientific work, is easier to understand, more reliable in its predictions, and ultimately far more useful than discussion and debate propped up by traditional data analysis techniques such as histograms, Pareto charts and spreadsheets. System Dynamics is an analytical approach that examines complex systems through the study of the underlying system structure. By understanding a system's underlying structure, predictions can be made relative to how the system will react to change. These tools, which are user friendly, self-instructing and personal computer (PC) based, lead to the rapid comparative assessment of many different development strategies. This in turn results in the characterization and prioritization of sustainable development strategies that are the most cost-effective and result in minimized impact.

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