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Time-Related Sources of Model Failure

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Abstract

System dynamics provides a valuable format for exploring a system and for understanding the behavior of a system. Experience suggests that this particularly true for current and near-term planning. As the time horizon for models is extended and their role becomes predictive, their value generally declines as unmodeled factors exert influence. As a consultant in long-range planning and student in studies of the future, the author has found that the source of model failure generally falls into one of several categories. This paper identifies several common sources of model failure and discusses some steps that may aid in avoiding the problem.

Good system dynamic models often create strong confidence in users as a result of the transparency of their logic combined with their detailed output, particularly when historical patterns are faithfully reproduced. Good models contribute to deep understanding of an issue or topic and offer insight to those striving to understand systems or remediate problems. Experience indicates that much system dynamics work focuses on the current situation and near-term forecasts, where such models can be very accurate and useful. As the time-horizon for forecasts is extended and models are used for prediction, the validity of models (system dynamics or otherwise) invariably decreases due to omitted information and mechanisms. In order to build models that are more useful, John Sterman suggests "…modelers must also take care to search for and include in their models the feedback loops, and structures that have not been important in generating dynamics to date but that may become active as the system evolves" (Sterman 2000). The purpose of this paper is to explore the issue of how system models (and models, in general) fail and to suggest approaches for identifying possible oversights in predictive models.

As a long-term planning consultant and student in studies of the future the author finds that the sources of errors that creep into models over time tend to fall into a limited number of categories. The purpose of this paper is to explore four categories of modeling error and potential methods for avoiding or minimizing those errors:

- Fuzziness
- System Boundary Issues
- Emergence of New Loops and Mechanisms
- "Unforeseeable" Events

The author acknowledges that the suggestions offered generally increase the complexity of the model and that incorporating additional loops into system dynamics models generally diminishes the readability of the model, making learning from the model more difficult. This article does not suggest that models for understanding should necessarily be more complex. The focus is, rather, on identifying and incorporating parameters, loops, and feedback structures that are appropriate for the time horizon of the model under study. This paper uses both stock/flow diagrams and causal loop diagrams to describe the dynamics of the mechanisms under discussion.

Many of the methods suggested in this paper are standard methods used broadly in futures studies. A good introduction to the methods of futures studies is available online at http://crab.rutgers.edu/%7Egoertzel/futuristmethods.htm.

Fuzziness

The modeling of complex systems inevitably involves simplification, classification, and agglomeration as the identification of model components defies the application of rigid logic with crystal clear boundaries. The modeler clusters components and concepts using "natural" breaking points based on perception and need. The lack of uniformity in natural populations of tangible items leads to variation. Over time the nature and profile of the population within the component can vary in the real world, leading the true behavior to drift away from the model. This paper considers two sources of fuzziness:

1. Nonuniform model components and concepts
2. Simplified system structures

Each of these forms of fuzziness are briefly discussed.

Nonuniform Model Components. For the purposes of this paper it is enough to recognize that model components and concepts often contain a certain degree of fuzziness and that, over time, the fuzziness of those components and concepts may lead to model failure. A key challenge to users of system models is recognizing that reality is departing from the assumptions in the model. The primary solution would be that the assumptions within a model be made explicit such that users have an ability to recognize that the assumptions within the model (and the categories and concepts) are losing validity. This solution bears two realms of responsibility:

1. The designer – to document his assumptions clearly, and
2. The user – to test the model assumptions against real world information.

This process can be facilitated by a thorough analysis of model components and concepts during the model design to identify how each may be fuzzy. Knowing where the components and concepts are fuzzy allows the designer to tighten the model definition by explicitly stating the assumptions and characteristics of that component.

While designing models the designer should query the client or knowledgeables regarding the fuzziness of the model components. Items that may seem casually to be consistent may have tremendous variation. As an example, in modeling energy a designer might have crude oil entering a refinery or nation as a component and not be aware of the variation of crude oils. Estimating gasoline production be 55% of crude oil feedstock would not be unreasonable today. However, the amount of gasoline that can be produced varies not only as a function of the crude (generally over a range from 40% to 70%) but also with the specific abilities of the refinery. A model that worked well historically could easily drift away from usefulness if crude oil slates grew more asphaltic over time or as refiners diversify their refineries to utilize lower priced, less desirable crudes.

A second, and perhaps more striking example, involves the "value" of a dollar. An initial reaction is typically that "a dollar is a dollar." There would seem to be no fuzziness. And if a dollar is a constant, that would seem to imply that the impact of a dollar on the economy or on an individual might be uniform. Yet, this is clearly not the case. Ten thousand dollars of GDP resulting from the sale of a first car has a very different impact on both the economy and the individual involved than the expenditure of the same amount of money to replace a car.

Fuzziness abounds and is unavoidable in modeling. Modelers should take care to insure their bases are documented adequately so that users may be better able to recognize departures from those bases.

Simplified System Structures. System dynamics models are frequently used to understand the essence of a problem or issue and simplification can be very beneficial in that situation. However, as a model's purpose shifts from understanding to predicting, the dangers of simplification grow. On the other hand, detailed modeling of complex systems is often impractical and has been known to result in huge models that no one understands. The author suggests that success lies not in pursuing detail purely for the sake of completeness but rather in adding detail as appropriate. The key lies in recognizing what is pertinent and potentially a source of shifting system behavior. The remainder of this article addresses three facets of system departure due to structural shifts and methods for identifying likely factors that should be modeled.

System Boundary Issues

Setting appropriate system boundaries is a critical activity in building a meaningful system model and is routinely addressed by authors addressing the system dynamic modeling process. A common message of system dynamics modeling lies in setting the boundaries such that "only the essential features necessary to fulfill the purpose are left" (Sterman 2000). Brevity in system dynamics clarifies communication and emphasizes the dynamic significance of the relationships and parameters included in the model. The author would suggest that tight boundaries are especially appropriate for problem solving in relatively short-term and independent processes. As the time horizon for a model is extended, uncertainty increases and the realm of potentially significant exogenous (and overlooked) parameters and feedback structures grows. The appropriate boundaries for a systems model expand. Extension of the time horizon for a model should involve a reassessment of the boundaries of the model.

Oversimplification is a common source of model error (whether system dynamics or other). System dynamic models may be more vulnerable to oversimplification other than other disciplines due to the focus on brevity. (*Note: this comment is intended as a caution, not as a criticism. The brevity of system dynamics models contributes significantly to communicability and clarity of the model concepts and dynamics. As the role of the model shifts to predictive the significance of brevity declines as the emphasis on accuracy grows.*) Focusing on short-term loops in a system is clearly beneficial in understanding short-term dynamics. Omission of longer-term loops may have no impact on a short-term application of a model but could clearly threaten model value for longer-term applications. Figure 1 illustrates the essence of the situation in a system dynamics model.

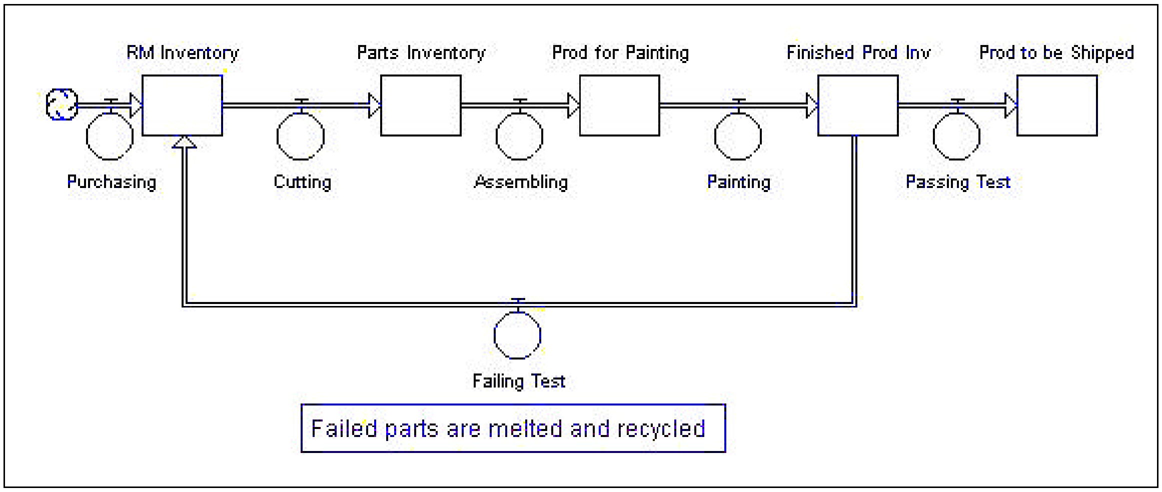

Figure 1 Simplified Manufacturing Process with a Potential Boundary Problem

Figure 1 depicts a high-level view of a simple production process with recycle of final products that fail quality control. If an **Assembling** capacity problem is being investigated, it would not be uncommon for the problem solving team to focus on the area where the problem lies – in this case **Assembling** – and exclude other areas as possible sources of the problem. Setting the boundaries of the models at **Parts Inventory** and the **Prod for Painting** may be adequate but there are clearly dynamics that can influence or even cause problems in **Assembling** that lie beyond those boundaries. (Note: a detailed **Assembling** model might include a number of parameters and loops which are aggregated in this example to emphasize the slower loop.)

The simplified high-level model of the global carbon cycle shown in Figure 2 provides a real-world example of a model where inclusion of loops is a function of the time horizon of the model. The loops in this model range from seconds to millennia. The times listed on the diagram show the typical period for the parallel loops operating from each node. Each of the flows in this model is substantial relative to the volume of carbon dioxide in the atmosphere. As a result, even a short-term model of atmospheric carbon dioxide should recognize all of the flows of carbon dioxide to the atmosphere – even if the flows from longer period loops are considered constant. Inclusion of longer period loops is clearly appropriate as longer time horizons are considered.

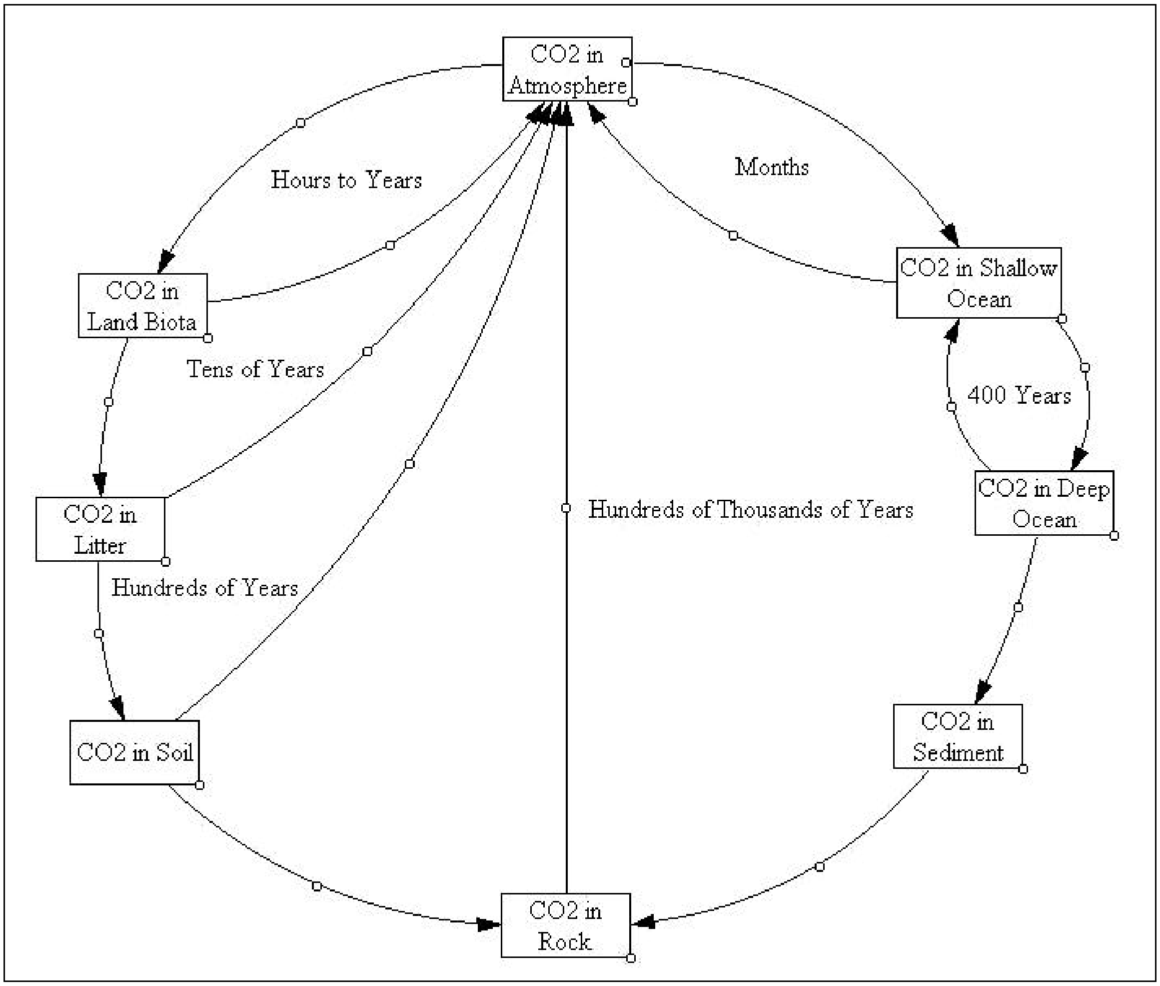

Figure 2 Simplified Global Carbon Cycle

The failure to recognize the need for broader model boundaries seems to generally result from one or both of two situations:

1. The modeler (or client) failed to recognize or consider broader bounds because the factors beyond the boundaries are beyond his control or lie in the realm of someone else's responsibility. Experience indicates that clients often fail to consider the systemic influences beyond their own realm of responsibility.
2. The modeler (or client) is unaware of the systemic implications of the broader issues – often as a result of lack of direct experience, or that the delay period on feedback loops in the real world are long enough that the modeler (or client) simply fails to recognize the effect.

Either situation can lead to building and adhering to simplistic, and potentially troublesome, models. While both situations need consideration in most modeling exercises, it is imperative that they receive extra consideration when the model is to be used to investigate long-term dynamics. One additional cause of oversimplification deserves mention.

3. The model was developed for short-term use but is used beyond its useful life. Good models often work well enough that clients continue to use the model over an extended period of time. Over time the limitations of the model are often lost. Parameters are not updated. Longer-term loops remain absent, and the value of the model declines.

Large, slow feedback loops that can readily be ignored in short-term modeling can easily dominate longer-term behavior. Modelers working on long-term models should pay particular attention to the term of the model and should be cautious of excluding loops which have cycle times of the magnitude of the model term or shorter. Where the model is predominantly focused on the longer-term, it would be wise to actively search for loops that have the ability to impact on the system under study.

John Sterman (Sterman 2000) and others have addressed the topic of boundary adequacy tests and tools and procedures for identifying problems. Several additional methods may be found useful in developing longer-term models:

- Seek diversity in input to the model to insure pertinent insights are included
  - Strive to represent all stakeholders in the model – don’t restrict input to the focal area of the model.
  - Seek knowledgeable people outside the boundaries of the model – start with people one step beyond the model bounds. (Example: the customers of your customers, or your supplier’s supplier, or manufacturers in semi-related industries)
- Watch for large, slow loops whose loop delays are of the same magnitude as (or shorter than) the term of the model or are erratic.

Short-term loops may, or may not, continue to be important to the behavior of longer-term models. It is the author’s experience that, as a generalization, positive feedback loops will continue to be important while negative feedback and short period equilibrium cycles may possibly be omitted or simplified without impacting on long-term model behavior. However, the importance of negative feedback loops in limiting positive feedback should not be overlooked.

Emergence of New Loops and Mechanisms

A second, common cause of system model failure involves the emergence of new loops that either enhance or diminish the role of previously existing system loops. Three primary sources of system evolution are identified:

- Exploitation of System Byproducts
- Exploitation of System Induced Demand
- Penetration by External Systems

Exploitation of System Byproducts. One of the more common mechanisms of system evolution involves the creation of new loops based on byproducts from an existing process within the system. All physical and many virtual processes include inefficiencies that generate waste byproducts. Over time byproducts tend to accumulate, creating a stock of potential feedstock to be exploited in some new process. Common examples from the business world include waste heat from production processes or unwanted byproduct chemicals in chemical manufacturing. A less tangible example would be growing envy of those who are financially successful by those who are not. In nature, the exploitation of such byproducts is one of the key drivers of biological diversity. In business processes byproducts are often a source of opportunity. In human nature, byproduct emotions may be one of the drivers of social change.

Figure 3 illustrates byproduct generation as waste. In industrial processes the waste is often a degraded form of the raw material or product. At other times it may be a low value byproduct including the raw material. In biological systems the waste is often an excretion.

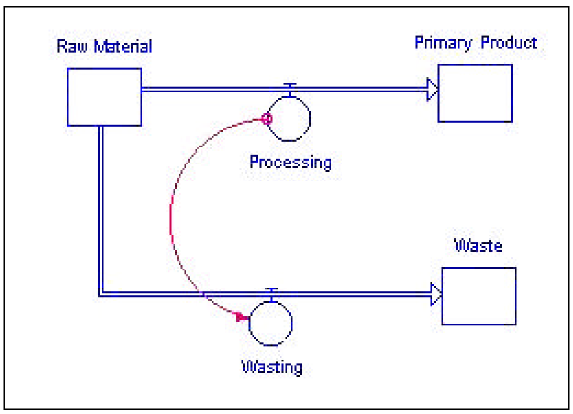

Figure 3 Accumulation of Waste Byproduct

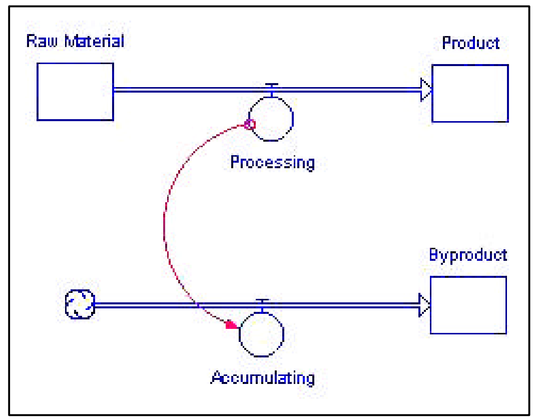

Figure 4 Accumulation of CoFlow Byproduct

Figure 4 shows a typical coflow generation of a byproduct. Common industrial byproducts include waste heat, used lubricants, worn and broken equipment, contaminated processing chemicals, contaminated soil, and employee attitudes. Biological byproducts include shade, toxins, detritus, fertilizer, and soil retention. Virtual human byproducts include boredom, envy, motivation, and frustration.

A key to recognizing opportunities for exploiting system byproducts lies in methodically examining each process in the system with particular emphasis on byproducts. The larger the byproduct flow and accumulation, the more practical is the exploitation of that byproduct. Experience indicates that individuals who work within a system often show difficulty in recognizing the potential value of their byproducts – they become accepted as part of the process. When seeking to recognize potential byproducts one should seek to involve a broad range of knowledgeable individuals in the process, being sure to include peripheral knowledgeables who may be more likely to recognize the value of a byproduct than those intimately involved in the process.

Exploitation of System-Induced Demand. Exploitation of system-induced demand is a special case of exploitation of system byproducts in which the system byproduct is a demand that is either not addressed or of interest to the original system. When the induced demand reaches a sufficient level it will attract the attention of an exploiter. The actions of the exploiter introduce new mechanisms to the system periphery. The alternative product may, or may not, compete with the original product. Over time the new mechanisms may come to impact on the original system – either positively or negatively. Figure 5 illustrates exploitation of system-induced demand where the exploitation impacts negatively on the original system. The use of a dashed line connecting **Introduction Of Alternative Products** to **Primary Product Sale**s in Figure 5 recognizes that the **Introduction Of Alternative Products** does not always impact on the original system. The **Introduction of Alternative Products** may introduce causal paths in several directions – none of which are illustrated in Figure 5.

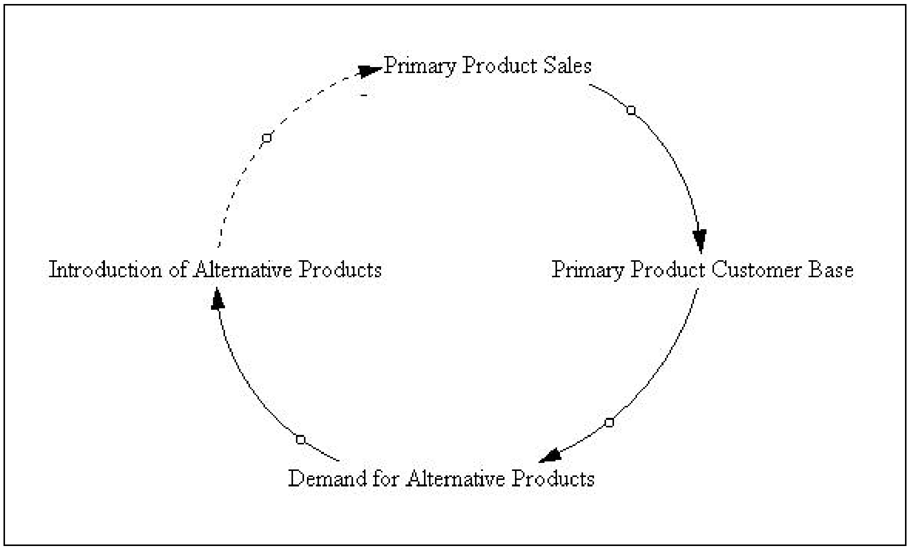

Figure 5 Exploitation of System-Induced Demand with Negative Impact

Three noteworthy outcomes exist for exploitation of system-induced demand:

1. Satisfaction of the induced demand may have little or no impact on the original system
2. The induced demand (and products to satisfy it) may become so strong that the induced demand ultimately becomes the driver (or a codriver of) the new "combined" system.
3. Satisfaction of the induced demand can serve as a stepping-stone for the exploiter of induced demand to compete in the original business.

Some of the more dramatic outcomes of successful exploitation of system-induced demand include:

- the original business acquires the successful exploiter and integrates the new business into the old
- the new business grows to the point where it displaces or acquires the original business
- a chain of induced demands is created leading to whole new

Examples of these outcomes include airline acquisition of regional air carriers, the acquisition of Conoco by DuPont, and the boom of the personal computer peripherals illustrate these three respective outcomes.

A classic example of an induced demand lies in the early days of the automobile. The Stanley Steamer was the fastest car in the world, holding the land speed record of 123 miles per hour. It was sexy. It was hot. It was reliable. And it was the dream car for dreamers. The Stanley Brothers elected to maintain a high price to maximize profits and maintain prestige status. Unfulfilled demand led to over a hundred manufacturers of copycat steam driven cars. High demand encouraged Henry Ford to introduce the Model T. When Ford pursued a business model of passing manufacturing efficiencies of scale along by lowering prices, he opened the door to penetrating the market through lower cost. Despite the problems of the gasoline driven car, the steam engine had lost its edge and the automobile business shifted to gasoline. (*The full story is somewhat more complex as electric automobiles were also more reliable than gasoline during the early days. Gasoline engines were the least attractive option prior to 1910. Unfulfilled dreams played an important role in stimulating a fundamental shift in the system.*)

System induced demand can take several forms, ranging from demand for lower (or higher) priced, more (or less) sophisticated, smaller (or larger) versions of a product to creating the opportunity and demand for totally new products. Several patterns of system shift due to exploitation of system-induced demand exist:

- A new product creates a new market but the product does not meet everyone's wants and needs – generating a demand for the similar product. Often the barrier is price, and the makers of the new product resist lower priced products in hopes of maximizing profits or in hopes of discouraging price competition. Companies outside the market often try to fill the induced demand. This pattern will be referred to as primary induction in this paper.
- New products often create new opportunities and make additional new products feasible. This pattern will be referred to as secondary induction in this paper.

Advance recognition of system-induced demand generally involves recognition of unfulfilled needs. Identifying unfulfilled needs can be quite difficult as those needs may not have been recognized by the potential clients. In addition, the inducer of the demand, frequently deliberately ignores the induced demand, much as the Stanley Brothers refused to sell anything but "luxury," high-priced cars. Still, in striving to refine the longer-term predictions from models, one should examine the demands induced by the system being modeled. As suggested in other sections, diversity of thinking and fresh-thinking from outside the mainstream can be very beneficial in seeking to identify possible system-induced demands.

Penetration by External Systems. Penetration of a system results when an external system begins to exploit the resources of an existing system – either directly via a similar product, or indirectly via introduction of a potentially unrelated product that siphons off customers (such as television impacting on radios). A common biological example lies in introduction of alien species. Business examples include market entry by foreign companies, and market entry by companies not formerly involved in the market. Entry by recognized competition is rarely much of a surprise. Penetration by an external system is often particularly damaging when the penetration is a surprise entry. In the business world significant damage often occurs before the hazard is recognized. Recent business examples include personal computers redefining the role of mainframe computing and IBM, cable companies competing with telephone and internet service providers, and the internet competing with long distance telephone service. While some external systems are clearly a threat to an existing system, the individuals in an existing system will often deny that the external system represents potential competition. Recognizing potential impacts of external systems at an organizational level has three clear parts:

- Recognizing the potential impact of the external system by one or more individuals
- Communicating and sharing the potential impact across the organization
- Sharing belief of the potential impact

Experience indicates that some individuals within a system will usually recognize that the external system is a potential source of competition. Environmental scanning, trend tracking, and foresight methods can be used to improve recognition of emerging trends and systems that hold potential impact. The biggest problem seems to lie in organizational resistance to the perception of potential competition or impact. This resistance is often strong enough that individuals are discouraged from sharing their perceptions for fear of being criticized, ridiculed, or castigated. Overcoming this hurdle can be difficult and challenging. Unbiased outside experts are often useful in identifying potential penetrators as they are less likely to be stifled by internal paradigm limitations. However, they still face hurdles in getting the organization to seriously consider their suggestions.

Unforeseeable Events

Unforeseeable events are a third source of system shift and model error. While the term unforeseeable seems to imply that the impact cannot be anticipated there are important semantic issues to be considered. The general public tends to think of an earthquake in downtown LA or a massive eruption of Mount Ranier as very low in probability. A futures perspective suggests these events are a certainty. The general public perceives these events as unforeseeable because the timing is uncertain and the event is viewed as low probability over some personal horizon. However, as the time frame extends the probability grows from small to near certainty. A good knowledge of a system, its characteristics and its tendencies provides a good source for categorizing and recognizing potentially destructive unforeseen events.

Unforeseeable events typically disrupt systems by depleting a stock or by disrupting a flow. The typical means of disrupting a flow is achieved by damaging or depleting a stock. For example, an earthquake’s disrupting a flow of potable water might be achieved by damaging the stock of distribution pipe, by damaging the stock of processing equipment, or by precipitating another event that polluted the water source. While evaluation of the stocks and flows in a model can provide a basis for identifying events that might possibly impact the system, such analysis is likely to be incomplete and possibly trivial for models are dependent on far more stocks and flows than are likely to be included in any model. Numerous dependencies are simply taken for granted and not included in the model.

Two basic approaches exist for considering unforeseeable events, or wildcards as futurists generally call them. The two approaches are quite different and involve totally different paradigms. One approach would be considering the impact of a list of externally generated wildcard events upon the system under study. While practical for a practicing futurist who is familiar with a broad range of wildcards, experience indicates that those unfamiliar with cross impact analyses and wildcard analysis find this process difficult and slow. A better approach for non-futurist modelers is likely to lie in developing wildcard events pertinent to the model. This process requires a solid vulnerability analysis of the stocks and flows in the model. Comprehensive vulnerability analyses can be quite time consuming and, in the author's experience, tend to become reductionist with escalating focus on less and less likely possible events. Consideration of unforeseeable events benefits from a balance between reductive vulnerability analyses and higher level systems thinking. The author's approach has been to use the reductive analyses to identify specific weaknesses and to use the specific weaknesses to identify generic weaknesses in the modeled system. These generic weaknesses can then be considered and modeled as appropriate. For example, from a production process modeling perspective, a tornado striking a supplier's plant, a railroad strike, and a feedstock quality control problem may be agglomerated as a feedstock disruption. From a modeling and plant operation perspective it is possible that the best solution to all of these events may be very similar (depending on the nature of the process). The use of generic events has major advantages as the individual events it represents may be too improbable to justify individual analysis, but collectively the individual events can be considered and a general strategy for coping with that class of event defined. The end result is a stronger strategy.

Conclusions

This paper has sought to shed some light on sources of failure that are encountered as time horizons grow longer in predictive models and to suggest potential approaches for identifying areas of weakness in predictive models so that the weaknesses may be remedied. This paper was prepared as one step in a series aimed at developing a methodology for identifying tendencies in complex and uncertain systems. While this work falls outside of the traditional boundaries of system dynamics it shares a strong belief that structure influences behavior. This work extends that concept to suggest that structural characteristics can provide insights into tendencies in system evolution and vulnerability. This concepts related to sources of failure in this first paper should be mostly familiar to experienced system dynamics practitioners. The methods for identifying model weaknesses are those of a futurist who probably views the world with less certainty than most of the readers. Those methods will probably feel rather "soft" and uncertain to those of you totally accustomed to the rigorous world of mathematics but are offered in hope they will aid readers in identifying likely sources of breakdown in predictive models.

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