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VALIDATING A MANUFACTURING PARADIGM: A SYSTEM DYNAMICS MODELING APPROACH

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ABSTRACT

Logic tools from the Theory of Constraints (TOC) provide the ability to descriptively characterize the entity relationships responsible for a typical, although somewhat chaotic, manufacturing environment. Basically through one-to-one mappings, System Dynamics (SD) models are created from the TOC logic diagrams. Insights gained from exercising the SD models are used to establish a new managerial conceptual framework. This structure guides managers through the continuous improvement process relative to addressing either a physical, policy, or paradigm constraint in their production system.

1 INTRODUCTION

Having mastered the techniques of mass production, product distribution, and management of large-scale production facilities, American manufacturers entered the 1940's in a relatively strong position. They emerged from the Second World War in even greater standing as the undisputed global leader while much of the rest of the industrial world lay in ruins. Yet, the next fifty years has seen American manufacturers go from worldwide preeminence to concern over their survival in a number of highly competitive industrial sectors. As the manufacturing boom of the 1950's and 60's evolved into the manufacturing bust of the 1980's, it has become apparent that significant changes are needed to regain some of their previous stature (Hopp and Spearman 1996). During this same period, American companies have been involved in a series of management "revolutions", ranging from MBO [management by objectives] and MRP [material requirement planning] JIT [just-in-time] and LP [lean production] (Womack, Jones and Roos 1990). More recently, TQM [total quality management] and BPR [business process reengineering] have dominated management's focus on the need to continuously improve of work performing processes (Deming 1986, and Hammer and Champy 1993). Despite some well-publicized successes associated with these managerial approaches, the results from the majority of these improvement initiatives have fallen short of managerial expectations (Hammer and Stanton 1995). In short, faced with intense global competition, manufacturing companies in the U.S. have often found that they are not competitive relative to cycle times, have higher inventory levels than desired, and are unable to effectively meet escalating customer requirements. As a result, they have frequently encountered eroding market shares and diminishing profit margins.

Realizing the need for a systems approach to improvement in manufacturing organizations, Goldratt (1984) introduced the Theory of Constraint (TOC) through a five step focusing process. This approach requires the production system constraint to be identified and exploited along with the Drum-Buffer-Rope concept and buffer management to be implemented prior to elevating the constraint. Many of the firms adopting the TOC focusing process of ongoing improvement have reported effective gains in performance (Goldratt 1995). In one instance (Montero 1999), on-time delivery performance improved drastically from roughly 35% to over 90% in less than five months. Generalizing the results of the TOC approach to addressing problems in a production environment, Goldratt (1994) introduced the TOC Thinking Process as a set of five logic trees. As effective as the TOC five step focusing process has been for manufacturing companies, the Thinking Process, may offer considerably more potential for improving any type of system (Dettmer 1998). Moreover, he states that the primary reason for this broader potential and application lies in two fundamentally unique characteristics of the Thinking Process. In particular, (1) the capability to deal with relatively abstract quality and productivity problems manifested through paradigm or policy constraints; and (2) the ability to accommodate the interdependent relationship between components in a system. As a result, it is not surprising that the use of the logic trees associated with the TOC Thinking Process have gained considerable acceptance as a framework for implementing systems thinking.

Although providing a significant step forward in helping managers implement systems thinking in their organizations, there is one major drawback of the TOC Thinking Process, namely, its inability to capture the dynamic nature of today's manufacturing environment. In short, the relationships depicted in the TOC logic trees often appear to be linear and relatively static and, as such, do not fully represent the dynamic complexity inherent in modern manufacturing organizations. Due to this possible shortcoming, recommended changes resulting from the use of these logic trees could be potentially incorrect.

The purpose of this paper is to illustrate how managerial understanding can be enhanced through the coupling of the TOC Thinking Process with System Dynamics (SD) modeling. First, a brief description of a common set of interrelated undesirable effects or symptoms typically found in a generic manufacturing environment is presented. This section utilizes two types of TOC logic diagrams to comprehensively characterize the interrelationships between problem symptoms and the root causes or core problem. Following this is a short discussion of the fundamentals associated with System Dynamics modeling. Next, results from using the *ithink* SD software package (HPS 1996) to validate production system behavior as presented in the TOC logic trees are discussed. For the most part, the simulation results were consistent with those identified with the logic trees. Then some insights gained from an analysis of the simulation results associated with exercising the SD models are considered. This new understanding provided the basis for developing a conceptual framework for addressing the interrelated effects associated with a basic or core system problem. Finally, some conclusions are presented relative to the value associated with coupling a system-based computer simulation tool, System Dynamics, with the logic-based tools of a systems-oriented management philosophy, Theory of Constraints.

2 CURRENT MANAGERIAL DILEMMAS IN MANUFACTURING SYSTEMS

Most organizations offer significant challenges to effective goal achievement. Often it is a combination of interacting concerns and issues that is responsible for the so-called “managerial mess” (Ackoff 1986). While any organization can provide a challenge to management as a system of dilemmas, manufacturing systems provide a relatively formidable managerial obstacle. Goldratt (1996) identified a host of common problems often found in typical production environments that include late customer order shipments, excessive expediting, constantly changing production plans, high finished goods inventories, and long production lead times. The cumulative effect of these common concerns is that managers often find themselves engaged in constant fire-fighting, and as a result, management becomes an increasingly difficult task. Unfortunately, the reactions of typical production managers are often to consider these problems independently and to address them individually by developing a team to analyze, evaluate, and develop a unique solution approach for each problem. In reality, however, it is important to realize that these undesirable effects are often just symptoms of a more basic core problem, and therefore, need to be evaluated from a collective or holistic perspective. In fact, Goldratt (1990) suggests that it is not unusual to find that as much as 70 percent of all undesirable effects present in a manufacturing organization can be eliminated if the “core problem” is identified and neutralized.

To demonstrate the relationship between these common symptoms and the more fundamental core problem, Goldratt (1994) proposed a logic diagram, called the Current Reality Tree (CRT). A CRT is a cause-and-effect diagram which helps managers better understand the complex systems underlying the structure of their organizations. More important, it also provides a linkage between the symptoms and the core problems, which are often hidden beneath successive layers of cause-and-effect relationships between entities. Once the CRT is completed and the root cause identified, the system constraint is invariably exposed. It now becomes possible to identify alternative improvement scenarios. In order to validate the effectiveness of any proposed change, often the next step is to create a second logic tree called the Future Reality Tree (FRT). FRTs can be considered to be a roadmap to the future, and in some respects, they often appear to be a mirror image of the CRT. By showing logically how the proposed change will unfold in the future to eliminate the system constraint, the FRT serves the indispensable purpose of assuring management that the proposed change will indeed yield the desired system performance prior to investing the required time, resources, and energy during the implementation of change.

Using these two logic tools, the core problem underlying the typical chaotic manufacturing scenario has been identified as the constant conflict between the emphasis on good departmental performance and good plant-wide performance (Koljonen and Reid 1999). On one hand, managers are obliged to maintain good cost performance, and as such, there is constant pressure for efficient use of resources, which resulted in materials being released ahead of time in order to provide work to resources. This results in large amounts of inventory residing throughout the production system. On the other hand, managers are also faced with the challenge of maintaining good plant-wide performance, and therefore, assuring that throughput is protected by meeting most customer order due dates. This often requires significant expediting. Both high levels of inventory and constant expediting serve to amplify management's difficulties and the other undesirable effects associated with the typical chaotic production environment. Since there is no way to satisfy both mindsets, namely, the cost world and throughput world paradigms, within a single manufacturing system, the solution under the TOC approach is the elimination of the cost-world focus (Goldratt 1996).

As mentioned earlier, however, it is questionable that the seemingly static "if..., then…" relations as depicted in the CRT or FRT logic diagrams can fully capture the dynamic complexity of a system. While the TOC Thinking Process provides a well-structured framework to describing an organization's underlying cause-and-effect relations, what about the cumulative effects of multiple entities with their many cause-and-effect relationships? What about the feedback structure within a system and the effects of time delays? Can System Dynamics modeling provide some additional understanding that could help managers address these interrelated issues in an effective manner?

3 WHAT IS SYSTEM DYNAMICS?

System dynamics uses systems thinking as a conceptual tool for gaining insight into the structures that create the dynamic behavior often found in complex systems. In essence, as shown in Figure 1, a system's pattern of behavior primarily results from the interaction of three core factors: (1) the structure of the system, which is often expressed in the form of causal loop diagrams and/or stock-and-flow diagrams; (2) the frequency and duration of time delays in feedback loops; and (3) the extent to which information flows and work are amplified through the system's feedback structure. The behavior of a system can often be described through interrelationships resulting from this set of three core factors.

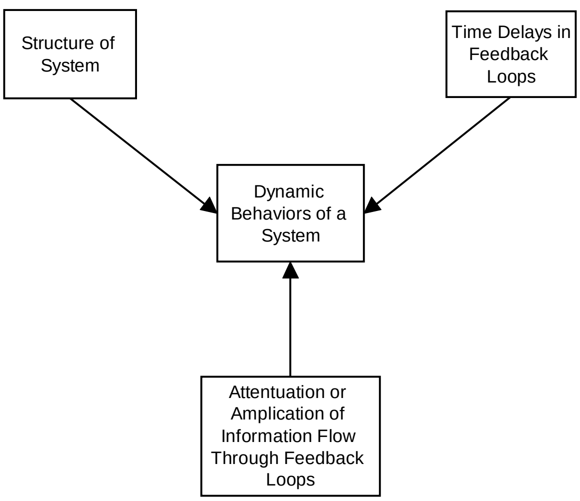

Figure 1: Dynamic Interractions within a System

Figure 2 shows an example of a causal loop diagram that depicts the deviation enhancing behavior that is captured within the generic manufacturing environment. In particular, pressure for the efficient use of resources requires that materials are released ahead of schedule which, in turn, increases management difficulties. Increasing management difficulties lead to a reduction of the time that management has available to deal with other issues such as effective inventory control and production planning. The latter then forces planning changes at a higher rate, which, in turn, increases managerial difficulties. A vicious circle of increasing management difficulties ensues.

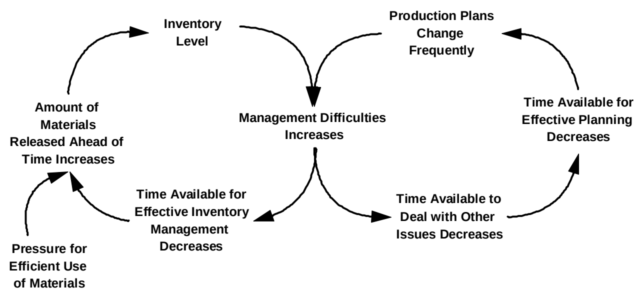

Figure 2: An Example of a Causal Loop Diagram

System Dynamics takes an integrative perspective to developing systems thinking capabilities through the use of computer simulation as a learning tool. The model-building process forces managers to consciously think about their assumptions of how the system works. Once the model is constructed, it is used to simulate how the system would behave over time. This simulation is useful because it creates a focus on the linkages between different elements of a system and on the feedback loop structure. This perspective can provide systemic insights that are often useful in the process of redesigning the system. Efforts to create new organizational structures often focus on exploring ways that the patterns of information flow may be altered. Modeling and simulation permit a semblance of systemic patterns and their dynamics. This generally provides users with deeper understanding of the effects resulting from the many inter-connections between the system's elements. After reflecting on why these patterns have emerged, managers and analysts can redesign the system and create another set of simulated results. Ultimately, this reiteration is able to promote insights and learning. The goal of this reiterative learning cycle is to help organizational leaders modify their mental models of their situations to account for the complex relations between structures, feedback loops, and patterns of behavior that would not be apparent otherwise.

Simulation has been an important part of science and engineering for many years. It is said that managerial systems contain as many as 100 or more variables that are known to be relevant and are believed to be related to one another in various nonlinear fashions (Roberts 1978). The behavior of such systems is very complex and is far beyond the capacity of human intuition to fully comprehend it. Forrester (1961) has argued that the cognitive limitations of human mind prevent people from understanding how complex dynamic systems operates. Computer simulation is one of the most effective means available for supplementing and correcting managerial intuition. It is a powerful conceptual device that can increase the role of reason at the expense of rhetoric in determining organization policy. It is a flexible tool that is comprehensive, unambiguous, and subject to rigorous logical manipulation and testing. In short, by incorporating the cumulative impact of feedback structures and time dependent relationships in a simulation environment, System Dynamics modeling provides a safe modality in which managers can test out their ideas and policy alternatives before implementing them within their organizations.

4 APPLICATION OF THE SYSTEM DYNAMICS MODELS IN A GENERIC MANUFACTURING ENVIRONMENT

A software package entitled *ithink* (HPS 1996) was used to create the SD model to validate the TOC logic trees for the generic manufacturing environment. Basically, building the SD models involved performing a one-to-one mapping of the entities of the CRT and the FRT to a stock-and-flow diagram. An *ithink* model is depicted as a stock-and-flow diagram with four basic building blocks: stocks, flows, converters, and connectors. System activities are reflected as flows in and out of a stock. Stocks are reservoirs that accumulate system flows and that collectively represent the state of a system at a given point in time. In the generic manufacturing environment, stocks represent the undesirable effects of the common problems, such as high inventory level, excessive expediting, and late customer order shipment, etc. Flows represent the changes in these undesirable effects. Since non-material flows are never conserved, a "cloud" is attached to the end opposite the stock that represents an infinite source for the flow. A solid arrow into the cloud means that the flow can be into or out of the associated stock. Because reinforcing loops intensify change, they always link one stock to a flow which, in turn, coupled to another stock, etc., thereby attenuating the magnitude of the overall effect. Whereas feedback loops add dynamic complexity to the system, converters reflect the detail complexity. Converters are often computed and serve as intervening variables in the close loops that connect stocks to flows. Since connectors provide the linkage between different system components, they reflect the modeler's assumptions about the cause-and-effect relationships underlying the system that is being modeled (HPS 1996). A schematic representation of the first SD model mapping of the CRT is shown in Figure 3.

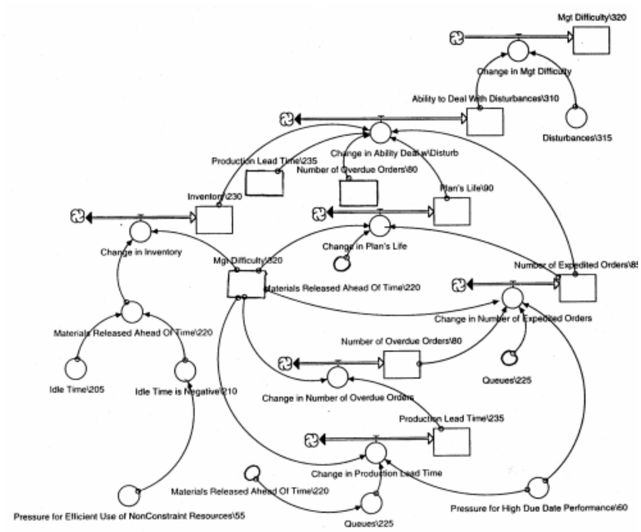

Figure 3: Current Reality Tree

After the model was constructed, the validity of its underlying logic as represented through the entity relationships was tested by running a wide variety of scenarios to determine if the situation predicted by the CRT could be simulated. Not surprisingly, the unstable system as depicted by the TOC logic tree was replicated. That is, the level of inventory, the number of expedited orders and overdue orders, and as a result management difficulty, kept increasing, while the life of the production plan and the management's ability to deal with disturbances were showing a decreasing trend. Table 1 shows the simulation results under this scenario.

Next, the effectiveness of the proposed change of eliminating the cost-world paradigm as illustrated in the FRT was validated. To simulate the elimination of the cost-world focus, this step was achieved easily by simply setting the "pressure for efficient use of resources" to zero. Again, the model was run to see if the system was able to maintain a stable state as it was predicted in the FRT. As expected, by eliminating the cost-world focus, the SD model produced results that are reflective of a stable system, namely, on-time shipment of most orders, little expediting, zero inventory, stable production plans, acceptable production lead time, managerial ability to deal with disturbances is not deteriorating, and management difficulty, on the other hand, is not increasing.

Table 1: Simulation Results of the Current Reality Tree

Weeks	Ability to Deal With Disturbances\310	Disturbances\315	Inventory\230	Mgt Difficulty\320	No. of Expedited Orders\85	No. of Overdue Orders\80	Plan's Life\90	Production Lead Time\235
Initial	5	3.91	0	0	0	0	5	10
1	4.95	3.3	13	0	0	0.75	4.84	10.09
2	4.83	3.58	26	0	0.04	1.77	4.67	10.24
3	4.66	0.51	39	0	0.14	2.8	4.51	10.46
4	4.42	3.93	52	0.07	0.32	3.86	4.35	10.75
5	4.13	3.78	65.01	0.23	0.63	4.94	4.18	11.1
6	3.78	1.22	78.06	0.23	1.12	6.07	4	11.52
7	3.36	1.9	91.11	0.29	1.8	7.25	3.82	12
8	2.89	1.13	104.19	0.69	2.72	8.48	3.63	12.55
9	2.34	4.74	117.35	1.17	3.97	9.77	3.43	13.18
10	1.74	1.08	130.7	2.38	5.7	11.15	3.2	13.89
11	1.06	2.72	144.17	2.4	7.91	12.61	2.94	14.68
12	0.3	4.98	157.72	4.03	10.58	14.17	2.66	15.53
13	0	2.29	171.75	6.67	14.19	15.86	2.32	16.51
14	0	4.81	186.35	9.96	18.88	17.71	1.92	17.6
15	0	2.17	201.56	12.07	24.78	19.74	1.44	18.82
16	0	4.2	217.18	14.22	31.78	21.93	0.87	20.15
17	0	1.84	233.27	16.72	40.02	24.31	0.19	21.59
18	0	4.34	249.72	18.1	49.51	26.87	0	23.13
19	0	3.7	266.61	21.34	60.42	29.63	0	24.77
20	0	0.18	284.11	24.93	73.06	32.62	0	26.55

However, there is one exception to this otherwise seemingly stable and uneventful manufacturing system. As long as the disturbance level in the system was assumed to be a random variable that could not exceed the value of management's ability to deal with the disturbances, there was no problem. Yet, if the disturbance level was set to be a random variable with a maximum limit which is greater than the management's ability to deal with the disturbances, then even though the cost world paradigm was eliminated altogether, the system would remain unstable. To be specific, as soon as the random disturbance is at a level that is higher than the management's ability to deal with it, the system reverts to a chaotic state. It appears that this situation triggers a series of intensifying actions on the undesirable effects through the feedback loops that propagate throughout the production system.

5 SOME INSIGHTS GAINED FROM THE SD SIMULATION MODELS

This interesting insight gained from the SD modeling under this exception case forced a rethinking of the original logic underlying the CRT. In another words, the core problem may not really lie in the cost-world paradigm itself. Furthermore, even if the cost-world paradigm may be correctly designated, as was proposed by Goldratt (1996), how realistic is it to try to change it? Cost-world thinking has been a well-ingrained paradigm of our society for over 100 years. How probable is it to expect a paradigm shift of this magnitude in most organizations? Carl Jung (1936) proposed that cultures possess a collective memory, and that people are never really conscious of these concepts and their influence on thinking and decision making. Moreover, some people believe that deeply-embedded paradigm that guides their thinking may be acquired through heredity. Thus, it appears unlikely that any single group of people, namely, TOC advocates, could change the dominant worldview of production management systems. Beckett (1973) has argued that throughout history worldviews that contradicted the dominant views have been largely ignored. In short, it would be extremely difficult to change a predominate worldview. Hence, rather than struggling with attempts to change a paradigm which has been an important foundation for societal thinking during the past century, the solution may simply lie in changing the translation from the paradigm to policy. In another words, there appears to be essentially three different types of constraints in a system: (1) physical, (2) policy, and (3) paradigm. To break a constraint in any given system, one should start methodically from the easiest or physical constraint, then moving on to a policy constraint, and finally addressing the paradigm, the most difficult constraint which may be impossible to overcome. Figure 4 utilizes this 3P concept of sequentially addressing the constraints from the easiest to the most difficult within the TOC purview of constraint elevation.

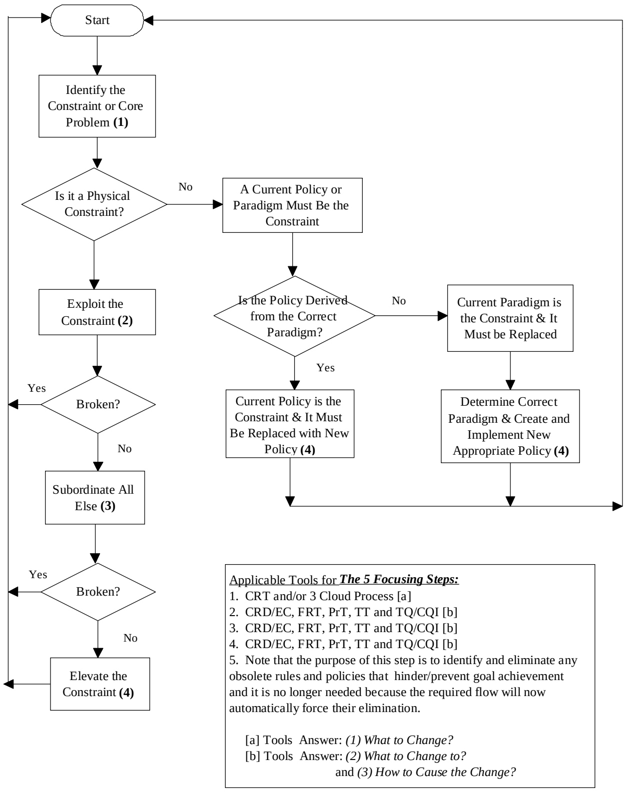

Figure 4: Breaking the Constraint - The 3P's Perspective

6 SOME CONCLUSIONS

This paper has demonstrated that while the TOC Thinking Process represents a well-structured systemic approach to understanding organizational structure and its underlying cause and effect relationships, System Dynamics modeling provides a supplemental understanding relative to knowledge gained through the TOC Thinking Process. This occurs through three dimensions: (1) taking into considerations the effects of the dynamic response patterns within a complex system; (2) provides an opportunity for managers to test out various policy alternatives before actual implementation; and (3) quantitatively validate the qualitative conclusions drawn from using the TOC Thinking Process. Keep in mind that effective TOC Thinking Process-based action plan requires the correct identification of the system's constraint/core problem. However, as previously mentioned, there is an inherent shortcoming in using the TOC Thinking Process in that it lacks the robust capability to fully capture the dynamic complexity of today's organizations. Is there a high probability that the core problem as identified by the TOC logic diagrams is indeed the system's core problem? System Dynamics modeling efforts can provide an opportunity to validate the core problem identification that has been revealed through a CRT.

This paper has documented a situation where System Dynamics models have provided assistance in identifying where the TOC Thinking Process oriented solution may not be as effective as originally envisioned. Through computer simulation, System Dynamics (SD) modeling offers a complementary approach to better describe the complicated response patterns in a complex system. By coupling the logic-based tools from the TOC Thinking Process and System Dynamics modeling, managers can better understand why behavior occurs and gain a new perspective in the design of more effective organizational policies.

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