CHAPTER 1
RESEARCH BACKGROUND, OBJECTIVES, AND HYPOTHESIS

1.1 The Research Purpose

The purpose of this research is to introduce a methodological approach that combines the system dynamics (SD) paradigm (Forrester, 1961) with the measurement of productive efficiency (Koopman, 1951; Farrell, 1957; Charnes, *et. al.* 1978), to evaluate productive efficiency in a complex and dynamic environment. By developing this framework, I will be able to evaluate a system's productive efficiency, determine the drivers and levers of performance though a causal investigation of the system, prescribe the best operation practices for the system operating in a dynamic and complex environment, such as a transient period[1], and determine the system's anticipated behavior once equilibrium (or steady state) is achieved. I believe that the outcome of this research will yield a new system performance perspective from which decisions can be made more effectively.

1.2 Research Objectives and Contributions

The objective of this research is to provide the decision-maker with a framework that offers greater flexibility when measuring system performance in a complex and dynamic environment. This research will begin its scientific journey by searching for and finding a solution to the dynamic performance measurement problem. This will be accomplished by developing a framework that will encompass both dynamic and deterministic information within the same model. I believe that this modeling combination will allow the decision-maker greater flexibility when making decisions about performance management problems that occur within a complex and dynamic environment such as a transitional period.

[1] A transient period is defined as the period commencing when a disturbance is introduced into a system, and ending when the system achieves a new steady state of operations. A transient period is representative of a dynamic and complex environment because as the system changes over time to meet new requirements, the interaction of the many system components are complex. Examples of a disturbance include the start up of a new organization, and the introduction of new technology or process into an existing production process.

While the primary goal of connecting/combining of SD with the theory of productive efficiency is to enhance the information obtained about a system, there are several other notable contributions that may be achieved. First, a relationship is established that links systems dynamics and the productive efficiency methodologies and theories. This is accomplished in two distinct steps: (1) Expand the current static production axioms into a dynamic realm; and (2) relate these dynamic production axioms to the behaviors found in fundamental SD structures. By doing so, one will be able to determine which production axioms are relevant when the system structure or behavior is known, or will be able to postulate the system structure or behavior if the production axioms are known to hold. This provides the foundation of this research initiative (Vaneman and Triantis, 2003 (forthcoming)).

Second, traditional approaches to the measurement of productive efficiency have concentrated on the analysis of inputs and outputs, and generally dismisses the process of converting inputs into outputs as transformations which occur in a black-box. This study uses the SD approach to study issues within the black-box. System dynamics modeling is based on control theory, and is represented by a series of variables, linked together through causal relationships. These relationships provide new performance insights for dynamical systems by identifying levers and drivers of system performance. Researchers who study productive efficiency (Koopman, 1951; Farrell, 1957; Färe and Grosskopf, 1996) have typically ignored these causal relationships.

In addition to identifying the levers and drivers of performance, this approach allows for system performance results from previous time periods to be fed back into the production process. This is possible because the SD framework is based on information-feedback. This too represents a contribution to the science of measuring productive efficiency because current methods do not automatically allow for feedback to influence future production.

Third, this effort will require system performance data to be evaluated in a new light. To date, many formulations have been presented that provide a measure of effectiveness of production systems. Many of these formulations have viewed system behavior deterministically and stochastically with respect to a static system solution (e.g. Data Envelopment Analysis (DEA) (Charnes, *et. al*., 1978), and econometric approaches). Therefore this research incorporates the methodologies and theories of productive efficiency measurement into a SD model to understand the system's dynamic behavior. In order to accomplish this, a hill-climbing optimization algorithm that allows a dynamic framework to be optimized is developed and employed. This structure is critical when studying productive efficiency within a dynamic environment.

Fourth, this research defines the dynamic production frontier. To date, the production frontier has only been portrayed in the static sense. However, an investigation of dynamical systems shows that the production performance of the system varies between time periods within a time horizon. Thus, a static production view does not adequately define a dynamic production frontier plane. These dynamic production frontiers allow the decision-maker to understand the inputs and output mixtures as they are related to time.

1.3 Research Motivation and Value

As systems become more complex and time dependent, alternative methods for evaluating production system performance in a dynamic environment must be explored. The efficiency literature to date has primarily been interested in system performance measurement rather than causation, because it was thought that: (i) uncovering the pattern of efficient and inefficient practices should be paramount; and (ii) that the comparative advantage is with performance measurement and not determining the causal factors associated with system performance (Färe *et. al*., 1994).

Nevertheless, Färe and Grosskopf (1996) suggest the need to explore what is inside the black-box of production technologies to determine how inputs are converted into outputs, so that efficiency performance could be better understood. To this end, they developed a network technology model. In their model, they evaluate how multiple inputs injected into the production process, at multiple time periods, can produce multiple outputs. While this approach is evolutionary, it fails to evaluate the causal relationship that exists within the network. Additionally, I argue while this computational approach studies system performance over time, it only considers system in a steady state of performance, and does not consider non-linear relationships.

I believe that system performance is inherent within the system's structure and policies[2]. Thus if the system structure (inputs, information, processes, decisions, and outputs) is understood, the sources of good system performance can be replicated for future system design, and the causes of poor system performance can be corrected. Since policies are deep-seated within the system's structure, determining the causal relationships will provide a window to how system policies affect system performance.

The purpose of this research is to introduce a methodological approach that combines the SD paradigm with the measurement of productive efficiency to evaluate productive efficiency within a complex and dynamic environment. I have coupled this paradigm with the fundamental assumptions of production theory in order to evaluate the productive efficiency of a production system operating within a dynamic and non-linear environment. By developing this framework, I will be able to study combinatorial and dynamic complexity concurrently, determine the drivers of performance though a causal investigation of the system, define the best way to approach to maximize performance during a complex and dynamic period, and determine the system's anticipated behavior at equilibrium.

The mathematical approach suggested in this research is meant to be complimentary to, and not replace, current productive performance evaluation techniques. This methodology is designed to aid decision-makers in evaluating and defining the best courses of action for a complex and dynamic environment such as a transitional period, a period ignored by every other productive efficiency evaluation technology. To illustrate this concept of a transitional period, consider Figure 1-1. At time t_0, a disturbance is introduced into the system causing the system to seek a new steady state. The system performance resulting from a normal transitional phase shows the system eventually achieving a steady state, but accumulates significant performance degradation during the transitional phase. The more efficient path for achieving steady state operations is via the enhanced system transitional performance line. When this

[2] A policy in this research is defined as: a goal; an observed condition of the system; a method to express any discrepancy between the goal and the observed condition; and a set of guidelines of actions to take based on the nature of the discrepancy.

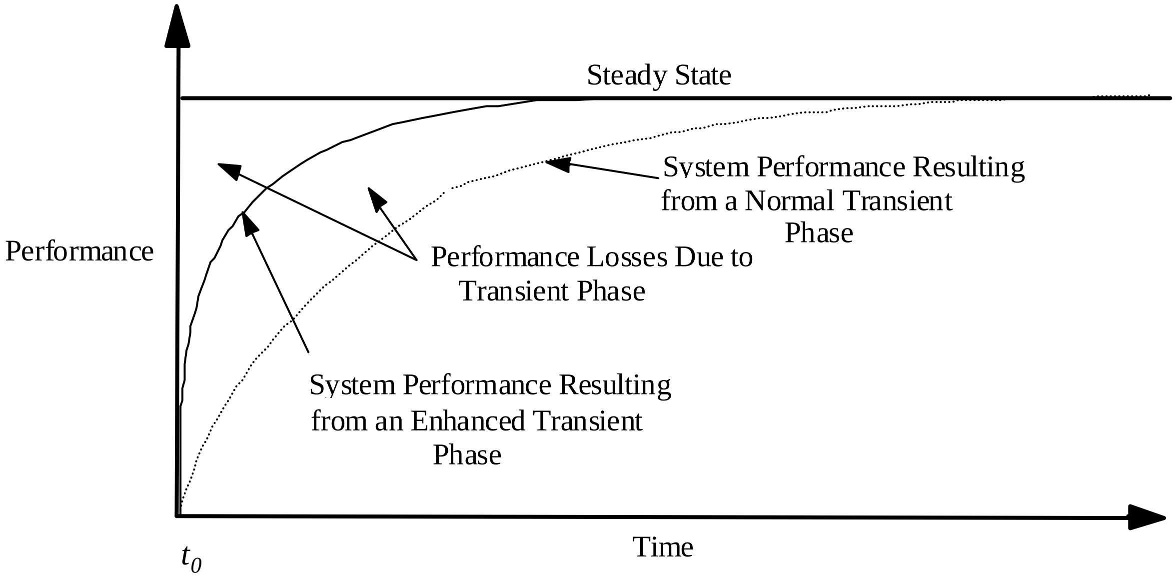

Figure 1-1. The Productive Efficiency Problem during a Transient Period.

approach is taken, performance losses due to the transitional period are minimized. I believe that this approach can potentially have a greater impact on policy decisions and how they affect system efficiency performance.

1.4 The Research Problem and its Sub-problems

The purpose of this research is to introduce a methodological approach that combines the SD paradigm with the measurement of productive efficiency. To accomplish this goal, this research combines the theory of productive efficiency with the SD methodology. However, this research goes much further than developing the framework. Before a complimentary framework could be built, I established the relationship between SD and the productive efficiency methodologies, theories and axioms (Vaneman and Triantis, 2003 (forthcoming)). The framework was later used in an implementation that addressed a real world problem.

The following sub-problems are associated with this dissertation:

Subproblem 1: Establish a relationship between the productive efficiency theories and methodologies and SD structures and behaviors. This includes: (1) Expanding the current static production axioms into a dynamic realm; and (2) Relating these dynamic production axioms to the behaviors found in the fundamental SD structures. By doing so, one will be able to determine which production axioms are relevant when the system structure or behavior is known, or will be able to postulate the system structure or behavior if the production assumptions are known to hold. This subproblem is discussed in Chapter 3.

Subproblem 2: Once the relationship between static productive efficiency theories and SD behaviors is established, one can expand these static theories into a dynamic realm. This includes showing how concepts associated with technical and allocative efficiency can be further defined in a dynamical system. A key aspect of this subproblem is to investigate how the production function behaves when injected into a dynamic environment, and what additional or complementary information can be gleaned concerning the performance of a dynamical system. This subproblem is discussed in Chapter 3.

Subproblem 3: Develop a framework that combines systems dynamics theory with the theory of productive efficiency. To successfully accomplish this task, productive efficiency methods and concepts must be successfully incorporated into a SD optimization model. This subproblem also includes investigating which productive efficiency methodologies and concepts can be employed in this environment and which cannot. This subproblem is discussed in Chapter 3

Subproblem 4: Demonstrate the utility of this new approach by evaluating a complex system research problem in a dynamic environment with the implementation of a real world application. This subproblem is discussed in Chapter 4.

1.5 Hypothesis

Hypothesis 1: The theory of productive efficiency can be extended into the dynamical realm by incorporating certain concepts within a SD framework.

Hypothesis 2: The new framework will provide insights into the performance of dynamic systems, plus provide additional insights about the drivers and levers of system performance.

Hypothesis 3: The framework developed will provide more complete and extensive information to the decision-maker as opposed to the information that can be gleaned through static evaluation means. This information includes:

A. An evaluation of strategic and tactical policies;

B. An understanding of the causal relationships within the system;
C. A measurement of past system performance and a prediction of future system performance;
D. Identify the best system performance and operating practices;
E. Identify optimal performance targets;
F. Additional insights and questions about performance measurement. (For example, this research may define an efficiency measure based on dynamic complexity, or some combination of dynamic and combinatorial complexity.)

1.6 Premises

The two fundamental premises of this research are: (1) systems are dynamic in nature; and (2) dynamic behavior of a system is a consequence of its structure. The underlying philosophy behind SD is that the behavior of a system is principally caused by factors endogenous to the system structure[3]. This is an important point since SD assumes that the causes of the problems must be within the system boundary (Richardson and Pugh, 1981).

The internal view of the problem often creates a much different focus on the problem than an external view. Internal views search for solutions to the problem that can be controlled within the system. External views of problems often search for variables to blame for poor system performance because it can not be controlled within the system (Richardson and Pugh, 1981). As an example, in the early 1980's the U.S. automotive industry blamed their loss of market share on an unfair balance of trade with Japan (an exogenous variable). In reality, their loss of market share was due to the inferior quality of their product (an endogenous variable).

Supporting the premise of dynamic behavior is the concept of system boundaries. System boundaries are important because these boundaries must include the variables that will provide the solution to the problem. If these variables are not included in the system, they are exogenous and therefore uncontrollable (Forrester, 1961). System boundaries force the problem to be viewed from within.

[3] The system structure not only includes the physical aspects of the system, but also the policies that govern the decision-making within the system (Roberts, E.B., 1978).

A second important concept of the dynamic behavior premise is variable interaction. System dynamics (and hence this research) assumes that causal relationships that exist between variables. These relationships are important when searching for root causes of problems or predicting the future system behavior based on policy changes. Causal relationships coupled with system boundaries leads to the third concept of dynamic system behavior premise – feedback.

A feedback structure influences a system by its own past behavior. Results from past decisions are realized in the future (Forrester, 1968).

A classic example to illustrate how system boundaries, causal relationships, and feedback relate to dynamic behavior is the heating system in a house. The thermostat is set to represent the system goal. As the room temperature deviates from that goal, the thermostat sends information to the furnace to turn on. The furnace heats the air until the observed conditions match the goal, at which point feedback is sent to the furnace to cease heating. The system boundary contains only the elements that are controlled by the system. The system does not contain reasons why the room is cooling (e.g. poor insulation, or an open window), because that variable cannot be controlled by the heating system. The variables in this example are causally linked. The thermostat relays the information to the furnace. Feedback exists because the thermostat sets the goal and measures the differences between that goal and the observed conditions, and receives and conveys information to the furnace about its actions.

1.7 Delimitations

One of the pillars of this research is the belief that this methodological approach will provide complementary system performance results to those derived from traditional performance measurement methods. The body of knowledge is plentiful with performance-related research and applications. The literature is also plentiful with theoretical approaches to dynamical systems. However, performance measurement in a complex and dynamic environment is noticeably absent. This research addresses inserting the fundamental concepts of performance measurement into a dynamic environment.

During the past decade, Färe and Grosskopf (1996) have attempted to rectify the methodological shortfall by developing their network technology model. However, while this approach is advertised as being dynamic, its underlying linear programming approach is arguably static.

The framework that has been developed during the course of this research is not envisioned to be an end-all solution to the dynamic performance measurement problem. Instead, this research focuses on investigating the utility of SD models, with incorporated optimization routines, as a viable framework for system applications where the goal is to measure system performance in a complex and dynamic environment.

As stated previously, the first step in this endeavor is to expand the static production axioms into the dynamic realm. By relating the production axioms to specific SD behaviors, one can address the assumptions about the production processes under examination through the observation of the system behavior. Current methods of evaluating productive efficiency lack the requisite information to understand the fundamental system structure thus lack the linkage to the production assumptions. I believe that this linkage is critical, because wrong assumptions about a system can lead to incorrect decisions about the course of actions to improve the system.

Second, this research ameliorates the measurement of productive efficiency by introducing a methodological approach that combines it with the SD paradigm (Forrester, 1961). I have coupled this paradigm with the fundamental assumptions of production theory in order to evaluate the productive efficiency of a system operating within a dynamic and non-linear environment. I believe that the true utility of this approach is that it provides the decision-maker with the understanding of the predictive impacts of specific endogenous variables to the system behavior in order to facilitate *ex ante* policy decisions, and provides a framework in which *ex post* root-cause analysis can be conducted.

1.8 Comparing Present Methodology with the Methodology Developed During the Research

Conventional performance measurement approaches (i.e. Data Envelopment Analysis (DEA) (Charnes, *et. al.*, 1978), the network technology model (Färe and Grosskopf, 1996)) employ linear programming as the computational base. These applications can be described as static, deterministic and discrete. While linear models offer an approximate solution (dues to their linearity) to a problem, they make the assumption that the organizational systems are adequately represented by linear analysis (Forrester, 1961 and 1987). Because of the definitive and relatively easy answers provided by the linear models, most organizations are willing to base their decisions on these solutions. However, most factors in an organization are admittedly non-linear. Because many organizations base their decisions on approximate linear solutions, I believe that many organizational systems are operating in a sub-optimized state.

System dynamics models use control theory as their computational base. These applications can be described as being dynamic, non-linear, continuous, and either deterministic or stochastic, depending on the model structure. However, to achieve system optimization, a heuristic (known as a hill-climbing heuristic) must be incorporated within the structure. Table 1-1 compares and contrasts the network technology approach and the SD optimization approach. While the network technology approach was designed to evaluate performance in a dynamic environment, the underlying optimization principles can be applied to other problem areas. The SD optimization approach has not previously been applied to performance evaluation problems, but will be shown in this research that it has wide applicability.

To illustrate the differences between the current state of dynamic performance measurement, and how this research expands that horizon, Figure 1-2 (Färe and Grosskopf, 1996) shows a comparison between the philosophy behind the network technology model (Färe and Grosskopf, 1996) and the philosophy of a typical SD model (Forrester 1961 and 1968; Richardson and Pugh, 1981; Sterman, 2000). The most notable difference between the two structures is the feed back mechanisms that exist in the SD model. One of the defining structures within SD models is the feedback loops, which serve to relay system state information from one time period to the next. The dashed lines in the figure represents the feed back loops from the process during the last cycle to the fixed and variable inputs ($x(f)$ and $x(v)$ respectively) of the current cycle. The feedback mechanism is of fundamental importance in SD modeling because it allows the system to adjust towards the desired goal, based upon system information gleaned from the previous period. The annotations in the figure are defined as:

t = the current time cycle

t-1 = the pervious time cycle

t+1 = the next time cycle

x(f) = fixed inputs

x(v) = variable inputs

P = system processes that transform inputs into outputs

y(f) = final system outputs

y(i) = outputs from one time period that are inputs to another time period.

1.9 Overview of Research Approach

The objectives of this approach will be achieved in six fundamental steps. Those steps are:

1. Review the static production assumption (axioms), and determine their relevance to the dynamic realm and structures and behaviors of dynamical systems. If applicable, the static production axioms into dynamic production axioms if applicable.
2. If applicable, define additional production assumptions that are only relevant to the dynamic behavior of the system.
3. Compare the properties of performance measures with the performance measure that results from the systems dynamics model. This comparison will be achieved by using the production properties found in Färe and Lovell (1978).
4. Formalize the model based the theory of productive efficiency and SD optimization techniques. In order to achieve this objective, the following activities are pursued: 1) Identify the system variables, causal linkages among the variables, and initial model conditions; 2) Define the system's production function; 3) Define the system constraints they relate to the system's resource utilization and the system's service achievement. 4) Obtain the results from the optimization routine and evaluate the policies based on these results.
5. Implementation of technology into a real world problem. The problem selected for this illustration is the implementation of new technology, and the effect that it has on productivity. A detailed description of the problem is deferred until Chapter 4.

Table 1-1. The Network Technology Approach vs. SD Optimization.

Attribute	Network Technology Theory	System Dynamics with an Optimization Heuristic Incorporated
Primary Authors	Färe and Grosskopf, 1996	Coyle, 1996[4] Wolstenholme, 1990
Goal	Decision-making based upon efficiency measurement, and estimation of the effects of policy change over time.	Decision-making based upon the behavior of the endogenous elements of the system with respect to efficiency measurement, and the simulated effects of policy changes over time.
Technical Approach	Optimization through linear programming using network technology.	Optimization through SD. (Heuristic approach).
Characteristics	- Dynamic - Deterministic - Linear - Discrete Time	- Dynamic - Deterministic or stochastic - Non-linear - Continuous Time
Advantages	- Linear programming approach guaranteed to find optimal solution. - Optimal solution is easily interpreted.	- Model represents causal relationships well. - Suggested policy changes are calculated and simulated over time. - The model allows for non-linear relationships. - Model allows for feedback within the structure. - Model can represent information flows.
Disadvantages	- Model does not allow for causal relationships to be defined - Policy changes and their effects are estimated (not simulated) and observed over time. - The model only accommodates linear relationships. - Does not allow for feedback within networks. - Does not allow for information flows to be modeled.	- Heuristic approach does not guarantee to find optimal solution. - Optimal solution is not always readily apparent.

[4] Coyle (1996) and Wolstenholme (1990) present discussions of optimization in system dynamics. Neither author considers the concept of incorporating the theory of productive efficiency within the SD models.

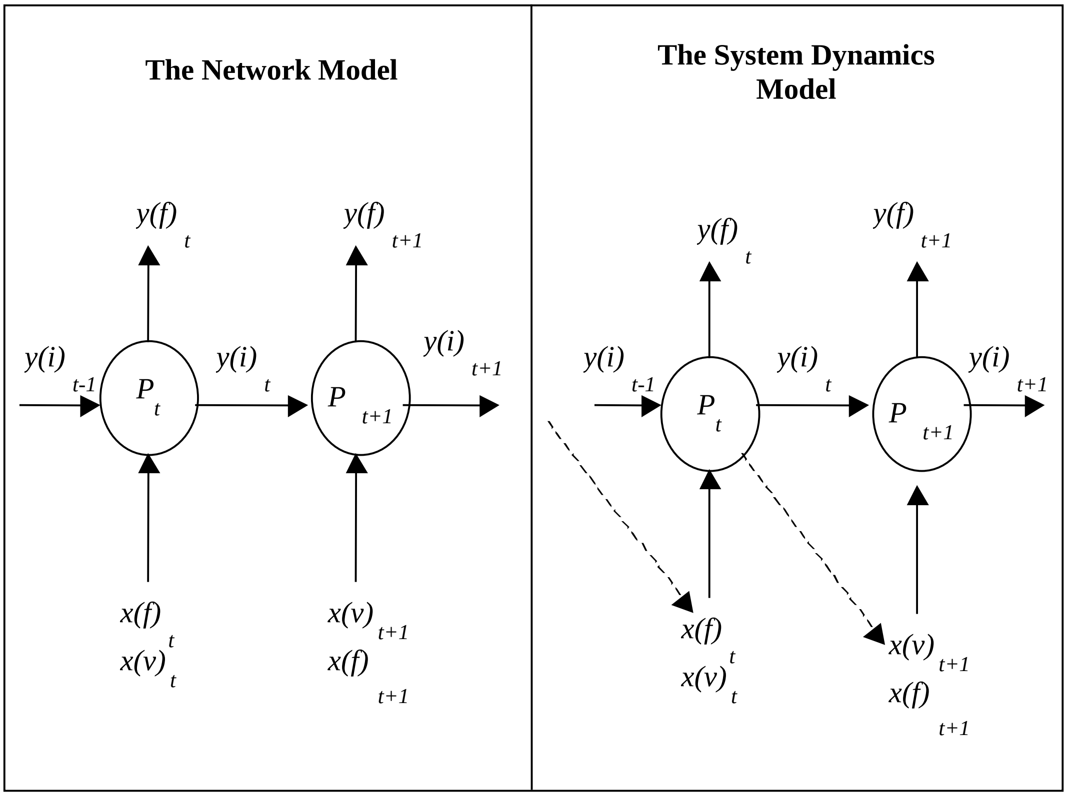

Figure 1-2. The Network Technology Model vs. the System Dynamic Model.