THE EFFECT OF DIMINISHING MANUFACTURING SOURCES ON LEGACY SYSTEMS USING SYSTEM DYNAMICS

By

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To my family and friends, for their endless encouragement, support, and patience.

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CHAPTER I

INTRODUCTION

A system, by definition, is composed of multiple elements [Kerzner 2003]. The loss of any one of these elements can impact the rest of the components in that system. Legacy systems, "any system developed in the past that are mission critical and whose failure can have serious impact on business" [Bennett 1995], are particularly vulnerable to such losses, yet such systems are becoming increasingly prevalent. Two examples are the B-52 bomber and the Boeing 747; both of which require the union of elements both human and nonhuman. The B-52 bomber project began in 1946 with an expected life cycle of only a decade [Bowers 1989] and is now expected to serve the U.S. Air Force up to 2045. The Boeing 747 whose production began in 1966 was intended for a lifecycle of only 25 years [Boeing 2006]. These examples, one commercial and one military, both lasted well passed their original design life.

The major question this research addresses is the impact of the diminishing supply base that will be available to support such legacy systems. The military refers to this as Diminishing Manufacturing Sources (DMS); "what happens when the sources for critical spares to support the system become scarce or non-existent" [Schramm, Littlewood, et al. 2003]. This problem will become increasingly important because it will occur more frequently as systems become increasingly technical and increasingly expensive; in fact it is predicted that 70-80% of the U.S. Military systems will be classified as legacy by the year 2010 [Drake 2003]. Also this research investigates the impact of various inputs, such as decreased supply base, and raw material availability, and how the fluctuation of these inputs, help or hinder other elements of the system and its support infrastructure.

In order to properly analyze this problem it is imperative to investigate the supply chain management for these systems. Supply Chain Management is the management of a network of manufacturers and service providers that work together to convert and move goods from the raw material stage through to the end user [Bozarth, & Handfield 2005]. The study and research of Supply Chain Management as it affects legacy systems shows not only what supply chains look like but also what variables impact the supply chain and how the variables affect that area [Forrester 1999]. This is crucial to the research because it allows the modeling of the impact on legacy systems when suppliers drop out of the supply chain and hence necessary parts, labor, and material become increasingly more difficult to find.

Research has studied short term supply chain disruptions; i.e. when the supplies are needed but not available [Hendricks, & Singhal 2003, Juttner 2005]. Examples of these short term disruptions are Sony’s inability to deliver Playstation 2’s for the 2000 holiday season due to part shortages; Nike’s inability in 2001 to match demand with supply due to complications in implementing supply chain management systems; and disruption in Ericsson’s ability to meet the demand for mobile phones in 2000 due to internal and supply production problems [Hendricks & Singhal 2003]. My research looks into the effects of long term systemic disruptions, such as those that occur when suppliers permanently leave the supply chain, as it occurs with Diminishing Manufacturing Sources. These types of disruptions form an inherent risk in a supply chain and the management of that risk is important to all members of the supply chain as the affects from a serious disruption can filter through many members of the supply chain [Juttner 2005]; formally, Supply Chain Risk Management can be defined as "the identification and management of risks for the supply chain to reduce supply chain vulnerability as a whole" [Juttner 2005].

In order to analyze the affects of these disruptions on legacy systems a modeling tool was needed that could allow the investigation of the strategic impacts of Diminishing Manufacturing Sources on Legacy Systems and offer a better understanding of dynamic interaction. The tool used was System Dynamics. System Dynamics is a method to enhance learning in complex systems, to help learn about dynamic complexity, to understand the source of policy resistance, and to design more effective policies [Sterman 2000]. System Dynamics was chosen because it allows the investigation of critical issues that Legacy Systems are faced with and illustrates the effects of Diminishing Manufacturing Sources on Legacy Systems Supply Chains.

The next section introduces the concepts of Diminishing Manufacturing Sources, Supply Chain Risk Mitigation, Legacy Systems, and System Dynamics as well as how these subjects are related. Section III introduces the modeling aims, approach and perspective. Section IV describes the modeling method including how the model was built and the structure of the model. Section V discusses the results of the simulation followed by a discussions section about the modeling structure and perspective, additional modeling approaches, the results of the simulation, and the availability of data. Finally section VII contains the conclusion as well as fertile areas for additional research.

CHAPTER II

THE IMPACT OF DIMINISHING MANUFACTURING SOURCES ON LEGACY SYSTEMS

To better understand this research is it imperative that background information is given on the main topics and terminology used throughout this paper. These topics are:

- Diminishing Manufacturing Sources
- Legacy Systems
- Supply Chain Risk Mitigation / Management

Each of these will be discussed in detail below and the links between these subjects is shown as well.

The concept of Diminishing Manufacturing Sources (DMS) originated with the U.S. Military more than four decades ago [Wilson 2002] and is defined by the Department of Defense (DoD) as "the loss or impending loss of manufacturers of items or suppliers of items or raw materials which may cause materiel shortages that endanger a system's or equipment's development, production, or post-production support capability" [Kobren, Melnikow, & Robinson 2005]. DMS deals with what occurs when suppliers permanently drop out of the market, for example Motorola, Philips, Intel and AMD who as of 1995 stated that they were in military components market for the long haul yet who exited that market in 1997, and more suppliers are in the process of doing so [Condra, Anissipour, et. al. 1997].

However DMS is not just a military problem. DMS is a problem for any system where the intended lifetime is much longer than those of the technology used within them, i.e. as the time between introductions of successive iterations of commercial components is decreasing the rate at which older components are discontinued is increasing [Condra, Anissipour, et. al. 1997]. An example of this is the amount of time to successive iterations of the Intel chip to market; the first chip was the 8080 and its successor was the 8086 which came out fifty months later, from there the time till the next chip, the 80286, dropped to forty-four months; more recently the time it took for the first Pentium chip to be released after the 486D2 was only 14 months, and usually due to the high demands for new products and the limitation of wafer capacity and cost, the introduction of a new product coincides with the discontinuance of an older one [Condra, Anissipour, et. al. 1997]. This shows that the longer a system is in service, the more vulnerable it may become to problems stemming from DMS.

Hence Legacy Systems (LS) are increasingly in danger of DMS due to the very definition of LS as systems that have been developed in the past yet remain crucial to the mission of the organization in which they exist [Bisbal, Lawless, et. al. 1999, Ransom 1998]. In the military it is predicted that 70-80% of their systems will be classified as legacy by the year 2010 [Drake 2003], and in the commercial sector, most systems are classified as legacy or become obsolete after only 6-18 months [Madisetti, Jung, et. al. 2000]. Another military example of a legacy system along with the B-52 example shared in the introduction is the Minuteman Intercontinental Ballistic Missile which was originally built in the 1960's with a design life of 5-7 years and has undergone continuous use and upgrades since that time [Schramm, Littlewood, et al. 2003].

Commercial examples of legacy systems abound in the realm of information technology; these can be database systems, payroll systems, accounting systems or any other type of software system that fit the criteria defined above for a legacy system

[Madisetti, Jung, et. al. 1999, Sneed 1995]. These types of legacy systems are expensive to maintain, often incurring 60-90% of the total life cycle cost for the system; additionally these types of systems have to face the problem of Diminishing Manufacturing Sources as well when the companies that created them decide to no longer offer technical support [Bennett, Ramage, & Munro 1999]. An example of this can be seen with the decision made by Microsoft to no longer offer any form of manned technical support for the Windows NT 4.0 Operating System. The mainstream support ended in 2002 and the extended support phase ended in July of 2003 leaving approximately 589,000 desktops around the United States and Europe without any kind of formal technical support [Computerworld 2003].

Given the fact that DMS can affect virtually any kind of legacy system it is important to understand and study the supply chain in order to understand the amount of risk inherent with these legacy systems [Houston, Concha, & Bohannan 1997, Littlejohn, DelPrincipe, & Preston 2000, Drake 2003]. In fact a cohesive supply chain management policy is even more crucial for a legacy system because such systems are not in volume production yet still need to be maintained and repaired [Wang & Zhang 2005]. In order to develop such a policy, an analysis of the system is usually conducted to determine the greatest areas of vulnerability [Evans, Towill, & Naim 1995]. Once these areas are discovered the next logical step is to create a simulation model and to run experiments to investigate the strategic impacts of DMS on a Legacy System and determine options on reducing vulnerability of the system this creates part of a Supply Chain Risk Mitigation (SCRM) strategy for the impact of DMS on LS [Juttner 2005, Stogdill 1999].

CHAPTER III

MODELING AIMS, APPROACHES, AND PERSPECTIVE

Modeling Aims and Approach

The structure of the model that was built in this research was designed directly from testimony from experts in the field of DMS and LS. It was not the intent of this research to build a model that yields precise data that can accurately predict and/or track real world trends. Instead this research created a specific strategic model to show the strategic impacts that certain key variables can have on the performance of the system as a whole.

A model that is capable of delivering these results is beneficial in that: it could be adapted to fit many different kinds of systems with minor changes to the pipeline and the variables, could be used as a starting point in many settings to test ideas, and it could also be used in the academic world as an educational tool to investigate if the model can be refined to mimic real world data and generate trends to forecast what could possibly happen in the future [Burgess 1998].

In the past many SD models have been created to analyze similar systems and supply chains [Sterman 2000, Forrester 1961]. For instance SD has been used to analyze the economic trends of US machine tool manufacturers [Anderson, Fine & Parker 1996], to study the service quality of a restaurant chain under pressure from investors [Van Ackere, Warren, & Larsen 1997], and various supply chains with system dynamics, theoretically as well as empirically [Towill 1991, Mason-Jones & Towill 1999], and a verified and validated a model of a real world supply chain [Del Vecchio & Towill 1990]. Our research is in that same vein. Using SD in this exploration is the correct choice for many reasons: the use of simulation allows for the replication of the initial situation, and the opportunity to investigate extreme conditions without risk [Pidd 2003], the use of simulation as a tool for analyzing and evaluating supply chain strategies has gained attention in recent years [Towill 1996b], and also many computer-based models developed in the field of supply chain management have use system dynamics as a tool for modeling and simulating systems with the help of ordinary differential equations [Puranek, Savit, & Riolo 1998]. More informally SD simulations allow for the systematic testing of supply chain strategies [Schieritz & Grobler 2003].

Using a discrete event simulation would not have been appropriate for this research given the fact that a discrete event simulation studies the system as the variables change instantaneously at certain points; discrete event simulations are concerned mainly with the start time and end time between the changes in variables and not the time in between [Oyarbide, Baines, et. al. 2003]. In order for this research to be of use, the model needs to encompass and simulate the dynamic environment in which these systems exist including how the model changes over time, not instantaneously. This ability is crucial because in the supply chains there are delays and the variables do not fluctuate instantaneously.

Modeling Perspective

The perspective of the model remains firmly in the realm of the impact of DMS on legacy systems. In order to assure this, the researchers went to experts who were faced with that problem. The experts confirmed that the appropriate variables, i.e. in the SCRM and DMS arena these are suppliers, manufacturers, distributors, and customers where in the LS world these would also include time, resources, and availability, were accurately represented and their influences linked in the appropriate way. This model focuses on the linkages between variables which will be in section IV and the pipeline through which the systems flow.

CHAPTER IV

METHODOLOGY

The Use of Experts

After a thorough literature review of the topic, a SD model of legacy system supply chains was built and used to analyze the risks that industry may be facing due to DMS. The data collected came from domain experts; professionals who work extensively in the field of DMS, LS, and SCM. The experts were also well versed in the needs of a system as a whole which includes, but is not limited to, hardware components, software, human interaction, and processes. This method was chosen so that the data collected came directly from practitioners who deal with the impacts of DMS on LS on a regular basis.

Two content experts consented to help with the research. All information was obtained via e-mails and telephone interviews conducted from July 21, 2005 – February 9, 2006. For system dynamics interactions an expert verified that the information taken from the content experts was correctly expressed in a functional model.

Data Collection from Content Experts

The first interview was spent introducing the experts to the topic of this research as well as the intended deliverables. Also discussed were their credentials, history, and experience in their field. One expert has over 31 years of work experience in steam, water, and power engineering, value engineering, and now holds the title of Chief of Industrial Operations Division working closely with value engineering and life cycle cost reduction. The second expert has 29 years of experience working with the Department of Defense (DoD.) He is currently the senior executive logistics manager for all Army aviation and unmanned aerial vehicles. Both of the experts had extensive knowledge and experience to draw on for this research.

After thirteen separate conversations explored the main topics found in the literature and how it related to the expert's work: i.e. methods for dealing with DMS in LS, the experts would begin to discuss their supply chains as well as where they feel they are most vulnerable along with the biggest areas of risk. After each conversation, the information was used to create and/or update the SD model. This model was built upon after every successive conversation. Before the next interview the most current version of the model was sent to the experts for comments on model structure. The experts advised where they believed the variables impacted, as well as variables they thought needed to be added, and variables believed to be superfluous. However after every conversation, we updated the model, the decision structure, or supply chain based upon their input. This ground-up, iterative, spiral process was used in building the model to assure the simple pieces were in place and appropriate before more complicated features of the model were added. Using this method allows different perspectives to be used to approach the analysis of the supply chain as well as the use of an interactive simulation to view the model and its behavior. This method also allows the model to be modified to different supply chains simply by changing a few variables and the impact they have upon the system.

Modeling Expert

In order to accurately harness the ideas and topics brought up during the interviews with the content experts it was necessary to ask for direction, advice, and help from an expert in SD to ensure that the appropriate structures and equations were used in the model.

These sessions were conducted with a local expert who studied under John Sterman at the Massachusetts Institute of Technology. The basic structure of these sessions consisted of going over the notes of the interviews together and then the modeling expert would make suggestions. These suggestions dealt with the structure of the model and appropriate equations to model the impact of the variables on the system. The researcher made sure that the model structure and impact of the variables were consistent with what was described by the content experts.

Model Structure

In order to become familiarized with SD notation and appearance of the figures a brief description will be given on SD model structure. The VenSim modeling software was used for this research.

The four main items in the figure about are the Stocks, Inflows/Outflows, Valves, and Clouds (see figure 01). The structure of all stock and flow representations are made up of these elements; their meanings are: Stocks are represented by rectangles (implying a container holding the contents of the stock), Inflows are represented by a pipe (doublelined arrow) pointing into (adding to) the stock, Outflows are shown by pipes pointing out of (subtracting from) a stock, Valves (shaped like an hourglass) control the flows, and clouds represent the sources and sinks for the flows; a source represents where the flow originates outside the scope of the model, and the sinks represent where the stock drains to after leaving the model boundary [Sterman 2000].

However not all systems can be modeled using only Stocks and Flows. There is need for auxiliary variables that influence the Stocks and Flows and create loops through which information is carried that affect other variables, Stocks, and Flows based on their polarity. The polarity of a relationship between two items signifies whether the independent variable reinforces or balances the dependent variable; more will be discussed on this below.

Auxiliary variables consist of functions of stocks, constants, or exogenous inputs and even though a model can be described accurately using only stocks and their rates of changes it is sometimes helpful for clarity and communication’s sake to use these auxiliary variables [Sterman 2000] (see figure 02). The auxiliary variable is noted by a label without a box around it and a solid single-lined arrow either pointing to the variable or pointing towards another item. At the head of the arrow there will be either a ‘+’ sign or a ‘-’ sign denoting the polarity of that causal linkage. That relationship will be described in further detail below.

The arrangements of the auxiliary variables and their linkages create loops. These loops are either called reinforcing loops or balancing loops depending on the polarity of the linkages within that loop. Determining what type of loop it is requires tracing the effect of a small change in one variable around the loop; if the feedback reinforces the initial change then the loop is reinforcing or positive, if the feedback opposes the initial change then it is a balancing or negative loop. Examples of both positive/reinforcing loops and balancing/negative loops can be seen in Fig. 2. The positive/reinforcing example is shown on the left hand side of the example. This is a reinforcing loop because as the birth rate increases, so does the population, therefore the bigger the population, the higher the birthrate will become (positive gain). The fractional birth rate variable has a ‘+’ polarity because it reinforces the birthrate, i.e. if the birth fractional birthrate falls, then the birth rate will fall, and vice versa. On the right hand side of the example is the balancing loop. As the population increases then the death rate will increase as more people pass away, hence the ‘+’ polarity on the linkage. As the death rate increases then the population will decrease, given this inverse relationship the linkage has a ‘-’ polarity (negative gain). Also as the average life time increases the death rate decreases. This inverse relationship also warrants a ‘-’ polarity.

Hence the link polarity defines the relationship and the effect that one variable has upon the other. Table 1 below gives formal definitions, mathematical explanations, and examples of these interactions (see Table 01).

Now that an introduction into model notation has been given, the model built in this research will now be discussed. First the system chain will be described; it is the basis for the model and illustrates the flow through which the systems travel. The supply base will be discussed afterwards which is the focus of this research and how it impacts the performance of the system chain, and finally a discussion on the other variables in the model that were added to make the model more realistic.

The System Chain

The first step in building the model in this research was to build the system chain. In this research the main object of concern are "systems." This means a system in its entirety from conception to phase out. An example of this would be the 747 as it was designed not only with the physical systems like the hydraulics and airframe, but also the training regiments that the maintenance and flight crews have to go through. The stocks that flow through this chain is a "system" as it progresses from concept, to production, to a current system, finally maturing into a legacy system and eventually either phase out or to an upgraded legacy system. These systems are the "products" of the supply chain (see Figure 03).

Starting on the left there is the inflow of *New System Development Start Rate* (NSDSR) into *Systems In Development*. This inflow determines the rate at which concept systems actually go into development. The *Systems in Development* (SID) stock begins with a certain amount of systems already in development. There are two outflows leading out of SID, they are the *Cancellation Rate*, and the *New System Development Rate* (NSDR). The Cancellation Rate was added to signify the fact that not all systems in development actually make it to full production. However the other systems that do are signified by the NSDR which is the inflow of systems into the *Current Systems* (CS) stock. Like the SID, the CS stock has a certain amount of initial systems already in the stock. From there the systems leave the CS stock at a set rate called the *Maturation Rate* on their way to becoming *Legacy Systems*. After the *Current Systems* have become *Legacy Systems* there are two paths which are available. The first is to be phased out, meaning that these systems are no longer needed and will be taken off-line. The second option for *Legacy Systems* is to be mission critical to the organization in which it is being used and deemed appropriate for upgrade at a rate determined by the *Upgrade Rate* into the *Upgraded Legacy Systems* (ULS) stock. The reason for these two paths is to model the behavior that managers must make when faced with a legacy system i.e. the legacy system can be taken off-line and replaced with a newer system, or the legacy system can be upgraded to increase its functionality and its lifecycle timeline.

For simplicity's sake the option to upgrade an already upgraded legacy system was not offered due to the complexity involved in keeping track of how many times certain systems have been upgraded. The model was constructed this way because of the increased difficulty that would arise in determining which systems were more appropriate to be phased out, those that have been upgraded many times or those that have been upgraded only a few times.

The Supply Base

The modeling of the supply base and it's affect on the system chain is the main focus of this research. The intent was to model the impact that the suppliers have on the system chain when the supply base decreases or increases (see Figure 04).

The modeling of the supply base was crucial to this research because it illustrates how the availability of New System Support and System Maintenance Support influence the flow of systems through the system chain. The term for Support used in both variables shown above represents the total amount of work that the contractors used in the creation and maintenance of the system can provide. The amount of work starts with a base number of systems that the contractors can provide for. This amount is called the

"Capacity" and is affected by the amount of systems that need to be provided for, versus the number that are being provided for at that time, and the average time it will take the contractors to handle the difference.

On the upper left hand side of figure 4 the number of new systems (NS) that need to be provided for is represented by the *Net NS Capacity Adjustment*. The number of systems currently being provided for is represented by the *Aggregate NS Capacity*, and the amount of time, in systems per year, necessary to make up the difference is represented by *NS Capacity Adjustment Time*. The *Net NS Capacity Adjustment* is the difference between *Systems in Development* and *Aggregate NS Capacity* over the *NS Capacity Adjustment Time*.

$$\textit{Net NS Capacity Adjustment} = (\textit{Systems In Development} - \textit{Aggregate NS Capacity}) / \textit{NS Capacity Adjustment Time} \qquad [01]$$

On the right hand side of figure 4 we see the same structure for current systems that need support. This is labeled as system maintenance (SM), which measures the amount of support available versus what is needed for total systems in the field

$$\textit{Net SM Capacity Adjustment} = (\textit{Total Systems} - \textit{Aggregate SM Capacity}) / \textit{SM Capacity Adjustment Time} \qquad [02]$$

The next piece of the supply base model is the *Effect of NS/SM Capacity on NS/SM Support*. This effect measures the difference in available capacity as modeled by the *Aggregate NS/SM Capacity* versus the needed capacity as modeled by the *Baseline NS/SM Capacity*.

$$\textit{Effect of NS Capacity on NS Support} = \textit{MIN}((\textit{Aggregate NS Capacity} / \textit{Baseline NS Capacity})\hat{}\,\textit{NS Capacity Elasticity}), 1) \qquad [03]$$

$$\textit{Effect of SM Capacity on SM Support} = \textit{MIN}((\textit{Aggregate SM Capacity} / \textit{Baseline SM Capacity})\hat{}\,\textit{SM Capacity Elasticity}), 1) \qquad [04]$$

For NS this baseline is determined by the number of systems in development and for SM this number is the *Total Systems* in use. The assumption is that there should be enough support for the total amount of systems being developed and/or being used, therefore the difference is taken between the *Baseline Capacity* and the *Aggregate Capacity*, raised to the *Capacity Elasticity Index*. This *Capacity Elasticity* shows how elastic the capacity is to change. If the index falls between zero and one then the capacity attempts to correct the deficiency. As in most situations this is the most likely scenario, and as the elasticity gets closer to zero, the more aggressive the correction becomes and as the number gets closer to one then the less aggressive the correction becomes. An index of anything greater than one and the capacity resists change to correct the difference. The *Effect of NS/SM Capacity on NS/SM Support* is a number between zero and one signifying 0-100% capacity for systems that need to be supported; hence the decision to use the "MIN" function. The *New System/System Maintenance Support Index* takes this number and multiplies it by *Raw Material Availability* and *Baseline NS/SM Support*. Both of these other numbers are values between zero and one signifying that there is anywhere from 0-100% of raw materials available and 0-100% of NS or SM can be supported.

*New System Support Index = Baseline NS Support * Effect of NS Capacity on NS Support * Raw Materials Availability* [05]

*System Maintenance Support Index = Baseline SM Support * Effect of SM Capacity on SM Support * Raw Material Availability* [06]

The *New System Support Index* then influences the *New System Development Rate* indicating how many systems can flow through that valve depending on the level of support; this relationship has a positive polarity. The *System Maintenance Support Index* (SMSI) must flow through another variable, The *Average Legacy System Lifetime*. This is due to the effect that SMSI must have on phase outs, i.e. as the support increases, the amount of phase outs in systems per year decreases because the *Average Legacy System Lifetime* increases.

The Stock Management Structure

Through the influence these variables exert on the supply chain we are able to model the impact that the diminishing amount of supply chain support available can have. However in order to make the model more realistic there are more variables and loops that need to be added. The next set of variables include, as Sterman names them, the “Stock Management Structure” which models the delays between orders and acquisitions and consists of two balancing loops: the "Supply Line Control", and the "Stock Control" [Sterman 2000] (see Figure 05).

The purpose of the Supply Line Control (SLC) is to adjust for the amount of supply already in stock and the amount of desired supply still needed; a delay is included to model the time necessary to make up the difference [Sterman 2000]. The SLC is a balancing loop made up of two variables, one stock, and one flow rate. The stock is called the Supply Line which in this model is represented by the *Systems in Development*. The two variables are the "Adjustment for Supply Line" and the "Indicated Orders" which are modeled as the *Systems In Development (SID) Adjustment* and the *Indicated New System Orders* respectively; and the rate is called the "Order Rate" which is the *New System Development Start Rate*.

The *SID Adjustment* is determined by two other variables: the *Needed Systems In Development* which represents the desired amount of systems in the supply line, and the *SID Adjustment Time* which models the delay necessary to make the necessary adjustments in order to compensate for the gap between the actual and desired systems in development. The *Needed Systems in Development* is influenced by two variables: *Average System Development Time* and *Desired Acquisition Rate*.

$$\textit{Needed Systems In Development} = \textit{Average System Development Time} * \textit{Desired Acquisition Rate} \quad [07]$$

The *Average System Development Time* determines how long it takes for a system to be developed and when the *Systems in Development* is divided by the *Average System*

Development Time the *Normal New System Development Rate* is obtained which determines the rate of flow from *Systems In Development* to *Current Systems*, i.e. the *New System Development Rate*.

$$\textit{Normal New System Development Rate} = \textit{Systems in Development} / \textit{Average System Development Time} \qquad [08]$$

The *Desired Acquisition Rate* is expressed in systems per year and models the amount of system acquisitions that are needed to make up for the loss of phase outs and the shortfall between the amount of current systems and the amount of desired current systems. When multiplied by the *Average System Development Time* we obtain the number of *Needed Systems In Development* to make up for these losses.

The *Desired Acquisition Rate* is also a key variable in the Stock Control (SC) loop. The purpose of the SC loop is similar to the SLC in that it allows the supply chain to adjust for the difference between the actual amount of systems in the field and the desired amount of systems in the field; also taking into account the amount of systems expected to be lost (phased out), adding that to the difference described above and then make the necessary adjustment for new system orders accordingly.

The stock of total systems in the field is modeled by the variable *Total Systems* which is the sum of *Current Systems*, *Legacy Systems*, and *Upgraded Legacy Systems*.

$$\textit{Total Systems} = \textit{Current Systems} + \textit{Legacy Systems} + \textit{Upgraded Legacy Systems} \qquad [09]$$

This number when taken from the amount of *Desired Systems* yields the *Total System Shortfall*, or the number necessary to make up for the difference between *Total Systems* and *Desired Systems*.

$$\textit{Total System Shortfall} = \textit{MAX}((\textit{Desired Systems} - \textit{Total Systems}), 0) \tag{10}$$

The need for the “MAX” function in this equation is to signify that there can be no less than a zero system shortfall. The delay in acquiring these systems is modeled by the *Stock Adjustment Time* (SAT). When the *Total Systems Shortfall* is divided by the SAT we obtain the amount of adjustment in systems per year that can be made, i.e. the *Total Systems Adjustment*; and when the *Total Systems Adjustment* and the *Total Phase Outs* (the sum of the Phase Out Rate and Upgraded Phase Out Rate in systems/year) are added, the *Desired Acquisition Rate* (DAR) is obtained.

$$\textit{Total System Adjustment} = \textit{IF:Total Systems Shortfall} > 0\textit{, THEN: \% Of Needed Systems Sent for Development} * (\textit{Total Systems Shortfall} / \textit{SAT}) \textit{ ELSE: } 0 \tag{11}$$

$$\textit{Desired Acquisition Rate} = \textit{IF: Total System Adjustment} > 0\textit{, THEN: Total Systems Adjustment} + \textit{Total Phase Outs, ELSE: } 0 \tag{12}$$

The DAR and the *Total System Adjustment* must be greater than zero as neither can represent a negative amount of systems. It would be unrealistic for the DAR to be less than zero; if a negative number was sent to the *Indicated New Systems Orders* then that would detract from the *SID Adjustment* which is in the Supply Line Control and not the

Stock Control thereby disrupting the flow of supply. The *Total System Adjustment* must be greater than zero as well due to the fact that when there is a surplus of systems then the method by which the model handles that excess is to phase systems out through the *Needed Systems* conduit. If the *Total System Adjustment* was allowed to be less than zero then the DAR would be less than zero and then not only would systems be phased out to handle the excess but fewer systems would be sent into development as well. In essence it would correct the problem twice, sending the system out of balance.

The DAR is then added with the SID Adjustment to obtain total amount of new systems needed to be placed into development. The link between the DAR and the *Indicated New System Orders* closes the Stock Control loop and finishes the Stock Management Structure. For simplicity's sake the figure below only shows the "Stock Management Structure" and how it affects the supply line; the Supply Base Structure (as shown above) has been taken out only to make the image easier to read.

The Upgrade Structure

The next portion of the model deals with the variables and information that are needed in order to make a decision as to whether or not a legacy system should be upgraded or phased out. Again for simplicity's sake the Supply Base has been eliminated from the figure (see Figure 06).

As seen in the model, the decision to upgrade a legacy system is impacted by five main factors: the amount of available support, the average lifetime of a legacy system, the amount of systems available to be upgraded, the urgency with which the upgraded need to be made, and the time necessary to upgrade a system.

The amount of support available for the legacy systems comes from the Supply Base and impacts the Average Lifetime of Legacy and Upgraded Legacy Systems. The *Average Legacy System Lifetime* is found by taking the difference between the *Maximum and Minimum Legacy System Lifetime*, multiplying that number by the SMSI, and then adding it to the *Minimum Legacy System Lifetime*.

*Average Legacy System Lifetime = (Maximum Legacy System Lifetime – Minimum Legacy System Lifetime) * System Maintenance Support Index + Minimum Legacy System Lifetime* [13]

By structuring the equation in this manner, the value for *Average Legacy System Lifetime* fluctuates appropriately with the amount of support. If the amount of support is close to zero then the *Average Legacy System Lifetime* will be close to the *Minimum Legacy System Lifetime* and the phase out rate will increase. Similarly if the maximum amount of support is available then the average lifetime will be near the *Maximum Legacy System Lifetime* and phase outs will decrease. This same equation structure is used to model the *Average Upgraded Legacy System Lifetime* with the difference that the *Maximum Upgraded Legacy System Lifetime* is higher than the *Average Legacy System Lifetime* given the fact that it has been upgraded and therefore should last longer.

*Average Upgraded Legacy System Lifetime = (Maximum Upgraded Legacy System Lifetime – Minimum Legacy System Lifetime) * System Maintenance Support Index + Minimum Legacy System Lifetime* [14]

The amount of support determines how many systems are available to be upgraded by influencing the amount of phase outs, i.e. if there is insufficient support to handle the systems today then there will not be enough support to upgrade the systems and sustain them into the future. Hence if there is sufficient support then more systems are available to be upgraded. However every legacy system can not be upgraded at the same time thus there is a threshold as to how many systems can be upgraded. This threshold, *LS Upgrade Threshold*, along with the amount of *Legacy Systems* yields a percentage of how many systems can be upgraded, i.e. *Fraction of LS Upgradeable*.

$$\textit{Fraction of LS Upgradeable} = \textit{Effect of LS on Upgradable LS(LS Upgrade Threshold / Legacy System)} \qquad [15]$$

When this variable is multiplied by the number of legacy systems then the actual number of legacy systems that can be upgraded is obtained; *Upgradeable LS*.

$$\textit{Upgradeable LS} = \textit{Legacy Systems} * \textit{Fraction of LS Upgradeable} \qquad [16]$$

In order to determine the upgrade rate, two values are needed. The first is the amount of systems that can be upgraded (*Upgradeable LS*), and the second is the *Actual Time to Upgrade*. The time needed to upgrade a system is dependent on two things. The average time to upgrade and the amount of urgency, or need for those systems to be upgraded.

The urgency in this case is a function of the *Needed Systems* which is the sum of the *Total System Shortfall* and the *Total Phase Outs*; the assumption being that there is a need to replace each system missing (system shortfall) and each system being lost (phase outs).

*Needed Systems = MAX(Total Systems Shortfall + Total Phase Outs * SAT, 0)* [17]

The *Needed Systems* is divided by the *Needed Systems Threshold* which is the benchmark for amount of urgency needed for these systems. As the *Needed Systems Threshold* increases it signifies that larger amount of systems can be upgraded and therefore there are more options to upgrade. However if the threshold decreases then a fewer amount of systems are available and the urgency increases. This urgency is modeled by the *Effect of Needed Systems On Normal Time To Upgrade*; as this number increases so does the *Actual Time to Upgrade* and vice versa.

Effect of Needed Systems on Normal Time To Upgrade = Needed Systems / Needed Systems Threshold [18]

The minimum and normal times to upgrade are constant variables. When the difference between the two is taken and multiplied by the *Effect of Needed Systems On Normal Time to Upgrade* and then added to the minimum time to upgrade, the *Actual Time to Upgrade* is then calculated.

*Actual Time to Upgrade = (Normal Time to Upgrade – Minimum Time to Upgrade) * Effect of Needed Systems on Normal Time to Upgrade + Minimum Time to Upgrade* [19]

When *Upgradeable LS* is divided by the *Actual Time to Upgrade* the *Indicated Upgrade Rate* is determined.

$$\text{Indicated Upgrade Rate} = \text{Upgradeable LS} / \text{Actual Time to Upgrade} \qquad [20]$$

Additional Variables

Additional variables are needed to make the model either more realistic or easier to use. The variables intended to make the model more realistic center around managerial decisions, i.e. the decision for how many systems to send into development and the decision to cancel a certain amount of systems. The variables intended to make the model easier to use are shown by instituting initial variables such as, *Initial Systems In Development*, *Initial Current Systems*, *Initial Legacy Systems*, and *Initial Upgraded Legacy Systems*. These final variables can be seen in the completed model shown in Figure 07 (see Figure 07).

The managerial decision that determines how many systems are sent for development is modeled by the *% of Needed Systems Sent For Development* near the bottom of the figure. The calculation is a percentage, determined by the modeler, of how many systems are actually sent for development. The purpose of this variable is to illustrate the fact that just because there are a certain number of systems that can be sent for development, it does not mean that they all will be sent for development. A similar decision is made in regards to if some systems should be upgraded and can be seen to the right of the *Upgrade Rate* labeled *% of Indicated Upgrades Made*.

Another real world variable is modeled in the *Fraction Development Lag Time Accounted For* variable. This variable models the ability of the managers to forecast a need for supply before the shortage is actually noticed. This variable is multiplied by the SAT to determine the *SID Adjustment Time* which is a fraction of the original SAT.

It was also important to model an accurate decision to cancel some of the systems in development. This decision was modeled by first determining if the *New System Development Start Rate* is zero. This is important because, if that rate is zero then there is no need for new systems to be made. Additionally the amount of *Needed Systems* has to be greater than the amount of systems being developed in order to avoid creating redundant supply. If both of these caveats are true then *Cancellation Rate* is determined by the *Systems in Development* divided by the *Average Time to Cancel*.

$$\textit{Cancellation Rate} = \textit{IF: New System Development Start Rate} = 0 \textit{ :AND: (Needed Systems – Systems in Development)} < 0\textit{, THEN: Systems in Development / Average Time to Cancel, ELSE: } 0 \qquad [21]$$

This cancellation rate will continue until there is a greater need for new systems.

The last variables that were added to make the model more realistic impact the *Desired Systems*. A *Baseline Systems* was created to illustrated a level at which managers would not like to see their stock fall below. This baseline is then impacted by an *Exogenous Demand Fraction*. This fraction represents all factors outside of the scope of the model that can lead the managers to increase their base level of supply.

$$\textit{Desired Systems} = \textit{Baseline Systems} * \textit{Exogenous Demand Fraction} \qquad [22]$$

In order to make the model more user friendly some variables were added to take the place of constants. This functionality was added to make the equations for some of the stocks easier to manipulate while the simulation are being run. These variables include *Initial Systems In Development*, *Initial Current Systems*, *Average Current System Lifetime*, *Initial Legacy Systems*, and *Initial Upgraded Legacy Systems*.

CHAPTER V

RESULTS

A Note About Scale

On the X-Axis of all the graphs the scale is in “Time Steps.” These time steps can be used to indicate any amount of time desired, from days to decades. These experiments were run on a time scale of years with each time step representing 6 months; however the decision to leave the axis as a generic “Time Step” stems from the lack of hard data to firmly link the experiments and results to the most appropriate time scale. However, expert testimony gave us sufficient data to base these experiments on a time scale of years. The decision to model each time step as 6 months adds additional granularity to the data hence at the end of the time scale, 100 time steps is the equivalent to 50 years. So, when instantiating the models with values we used the values that were most appropriate as were given by the experts.

Managerial Experiment Results

There were two experiments that dealt with the implementation of managerial decisions in the model. These were the effect of *% Of Needed Systems Sent for Development* on *Systems In Development*, which will be discussed first, and *% of Indicated Upgrades Made* on *Upgraded Legacy Systems* (see Table 02).

In the first managerial experiment (see figure 8) there are two important things to notice. The first is the tendency to correct the system shortfall quickly depending on the *% Of Needed Systems Sent For Development,* and the second is that no matter what percentage of systems are sent for development after approximately 10 time steps all the results converge to the nearly the same number. Looking at Figure 8 it is apparent that as long as some percentage greater than zero of needed systems are sent for development then the numbers will converge in the long run. The only trend line that does not converge is the curve that represents the *Systems in Development* when the *% Of Needed Systems Sent for Development* is 0%. This is due to the fact that if no needed systems are sent for development then the model can never correct the deficiency in the stock control.

These effects are due to the Stock Management Structure of the model and its ability to seek out deficiencies and correct them over time. The initial spike in *Systems In Development* seen when the *% of Needed Systems Sent For Development* is 100% shows a tendency to correct the problem as quickly as possible yet in the long run overshoots the goal and makes another correction later on to compensate for the initial increase in *Systems in Development*. As the percentages are reduced to a more moderate number *Systems in Development* adjusts gradually, not drastically as with 100%. Eventually equilibrium is reached in the model no matter what percentage of needed systems are sent for development.

The second managerial experiment deals with the impact *% of Indicated Upgrades Made* on the *Upgraded Legacy Systems* (see Figure 09).

The results from this experiment are more straight-forward yet there is one interesting thing to notice. The first is that no matter what the percentage is, after about 7 time steps have elapsed and the initial adjustment has been made to compensate for the percentage of *Legacy Systems* being upgraded, the trajectories disperse. This is due the inability of the *Upgraded Phase Out Rate* to adjust according to the number of *Upgraded Legacy Systems.* After several more experiments were run to investigate this phenomenon it was discovered that the greatest impact on the *Upgraded Phase Out Rate* came from the *Maximum Upgraded Legacy System Lifetime* (see Figure 10). This phenomenon is consistent with what was discovered below in the Legacy System Lifetime Experiments.

Legacy System Lifetime Experiment Results

To further investigate the impacts on the phase out rates, additional experiments were run which varied the *Maximum / Minimum Legacy System Lifetime* (see Table 03). Similar to the effects of *Maximum Upgraded Legacy System Lifetime* on *Upgraded Phase Out Rate, Maximum Legacy System Lifetime* appears to have the same effect on *Phase Out Rate.* Thus showing that the maximum lifetime for a legacy or upgraded legacy system is key to the rate at which those systems are phased out.

There is an almost exponential increase in the phase out rate as the lifetime drops. However in the results we see that there is a much wider dispersion after approximately 15 time steps than with the *Upgraded Phase Out Rate* (see Figure 11). These results also show the model's tendency to over-correct when the parameters are constricting.

The effect of *Minimum Legacy System Lifetime* on *Phase Out Rate* show that the smaller the minimum lifetime is, then the greater the *Phase Out Rate*, however this increases gradually over time and eventually stabilizes after approximately 40 time steps (see Figure 12). The increase in *Minimum Legacy System Lifetime* follows the same shape and a change in amplitude occurs indirectly with the minimum lifetime, i.e. as the minimum lifetime increases the *Phase Out Rate* decreases. It is also important to notice that the *Minimum Legacy System Lifetime* has a much smaller affect on the *Phase Out Rate* when compared to the effects of *Maximum Legacy System Lifetime* meaning that the service length of a system is determined less by a requirement set forth in the development process than by the systems maximum available lifetime..

The last experiment looked at the impact of *Minimum Legacy System Lifetime* on *Upgraded Phase Out Rate* (see Figure 13). These results follow the same pattern already shown above; that the model has a tendency to aggressively correct the imbalance in the system. As seen when the *Minimum Legacy System Lifetime* is approximately 1 time step the *Phase Out Rate* increases slightly within the first ~6 time steps, then decreases almost as dramatically to correct itself. When the minimum lifetime is increased then a more gradual correction is are made. After approximately 16 time steps, the trend lines converge.

Supply Base Experiment Results

Some of the Supply Base experiments also dealt with phase out rates; the effect of *SM Capacity Adjustment Time* on *Phase Out Rate*, and the effect of *SM Capacity Adjustment Time* on *Upgraded Phase Out Rate* (see Table 04). Looking at how the *Phase Out Rate* is affected by *SM Capacity Adjustment Time* the data shows convergence at the beginning of the time scale and at the end of the time scale. After approximately

10 time steps have passed in the simulation the widest dispersion between the numbers is no more than approximately 0.75 systems per time step (see Figure 14).

More interesting results are seen in the effect of *SM Capacity Adjustment Time* on *Upgraded Phase Out Rate*. These results further illustrate the model's tendency to overcorrect when the parameters are constricting or when the model has complete leeway to correct the problem without hindrance (see Figure 15).

As seen in figure 15 when the *SM Capacity Adjustment Time* is short then the system can adjust for demand more rapidly hence the subtle increase in phase outs when systems are no longer necessary, and when the *SM Capacity Adjustment Time* is longer then the system has to make more gradual adjustments. These minor adjustments help to balance the amount total systems. A phase shift also occurs at approximately 20 time steps and immediately afterward the trend lines converge. This phase shift occurs because of the impact that *SM Capacity Adjustment Time* has on the *Average Upgraded Legacy System Lifetime*. After the initial spike in *Upgraded Phase Out Rate* occurs, the model then takes into account the increased *Upgraded Legacy System Lifetime* due to enhanced *SM Support*. These longer upgraded legacy system lifetimes force the *Upgraded Phase Out Rate* to correct for the number of systems phased out prior to the enhanced support for legacy systems coming into effect (see figure 16).

The next Supply Base experiments dealt with the affect of *NS Capacity Adjustment Time* on *Current Systems* and on the *New System Development Rate*. As the adjustment time decreases the *New System Development Rate* makes a large correction for deficiencies early on and then self corrects. Similarly the data shows another correction. After the initial sharp increase in *New System Development Rate* is made a sharp decrease in that rate follows to compensate. No matter what the adjustment time is, after approximately 20 time steps all the trend lines converge to the same values and continue until the end of the time scale (see Figure 17).

This pattern then affects the amount of *Current Systems*. As the New System Development Rate increases then eventually so does the amount of *Current Systems.* As the data below shows, there is an initial correction for the number of Current Systems and then eventually equilibrium is found (see Figure 18).

CHAPTER VI

DISCUSSION

Managerial Experiment Discussion

The results from these experiments show interesting results for both researchers and practitioners. In the first experiment, the effect of *% of Needed Systems Sent for Development* on *Systems in Development*, should help practitioners realize that the percentage of new systems sent into development is important only for the near future because towards the end of the time scale it does not matter if 10% or 100% of needed systems are sent for development. In the end the supply chain reaches equilibrium regardless of how many systems are sent for development. So if there is an urgent need for systems to be fielded quickly, then this is a good option for filling that requirement, however if a large increase in systems over a long period of time is preferable, then manipulating the *% of Needed Systems Sent For Development* is not viable.

For researchers it is interesting to note that the data curves converge to practically the same value at the end of the time scale, which for these experiments is 50 years or 100 “Time Steps” of 6 months. The tendency of the model to find equilibrium is interesting because it shows that once the initial correction is made, the model “settles in” and it is difficult to change once this occurs. Researchers may wish to further investigate the resistance to change once equilibrium has been established by running more experiments on the model on a longer time scale to see what variables, if any, can disrupt the equilibrium once it has been established.

The second experiment, the effect of *% of Indicated Upgrades Made* on *Upgraded Legacy Systems* shows a different result in that the percentage of upgrades has a much larger effect on the number of systems in the long run i.e. 0% of upgrades made yields approximately 11 upgraded legacy systems and a 100% of upgrades made yields approximately 58 upgraded legacy systems. For practitioners this means that a surplus of upgraded legacy systems could occur if too many upgrades are made and the supply base that is supporting these systems could be spread too thin amongst a large number of Legacy Systems. Therefore practitioners should understand that it would be wise to select the systems to upgrade carefully because of the limited capacity of the supply base to support all legacy and upgraded legacy systems.

A researcher should notice that due to the dispersion of the data curves in figure 9 that there is a certain *% of Indicated Upgrades Made* that keeps the number of *Upgraded Legacy Systems* constant. This percentage is approximately 50%. It would be interesting to find if this percentage keeps the number of Upgraded Legacy Systems constant or if it is influenced more by other variables such as *Legacy Systems, LS Upgraded Threshold*, *Effect of LS on Upgradeable LS*, *Fraction of LS Upgradeable*, *Upgradeable LS*, etc… because then that variable and it's value that keeps the number of *Upgraded Legacy Systems* constant could be used as a benchmark value to start from when there is a desire to increase, decrease, or keep constant the amount of *Upgraded Legacy Systems*. This is important because it would allow a better understanding of what a system relies on in order to be upgraded and also because it would allow practitioners a greater ability to change the performance of their upgrade rate depending on what end result is needed.

System Lifetime Experiment Discussion

The collective results of these experiments show two findings. The first is that the *Maximum Legacy / Upgraded Legacy System Lifetime* has a much greater impact upon on system phase-out than on the *Minimum Legacy System Lifetime* [see figs 10, 11, 12, 13]. The second is that the Maximum Legacy System Lifetime has a much greater impact in the long run on *Legacy System Phase Out Rate* then *Upgraded Legacy System Phase Out Rate* [see figs 10, 11].

The first interesting result is somewhat counter-intuitive in it is typically assumed that by imposing a minimum lifetime requirement on a *Legacy* or *Upgraded Legacy System* would thereby determine the phase out rate for those types of systems. This model shows that in reality the maximum lifetime determines the rate at which these systems are phased out [see figs 10, 11]. Therefore the practitioner should not be concerned so much with the minimum amount of service required for these systems but the maximum amount of time such systems can function in the field. For example this length of time for an aircraft would be dictated more by the number of years the alloys used in the airframe can last before the fatigue of use begins to break them down as opposed to the minimum time the company that owns the aircraft would like to be able to use the aircraft.

Practitioners should also notice that the *Maximum Legacy System Lifetime* only affects the *Legacy System Phase Out Rate* in the long run. Figure 11 shows a wide dispersion in the number of systems at the end of the time scale; the values ranging from less than 4 systems per year to almost 14 systems per year. This dispersion does not occur with the *Maximum Upgraded Legacy System Lifetime* which has a large impact early in the time scale, i.e. less than 15 time steps, and eventually converge to roughly the same phase out rate at the end of the time scale. The difference in results is due to two factors. The first factor is that the *Legacy System* stock is being fed at a constant rate by the *Maturation Rate* of *Current Systems* meaning that there will always be a need for a higher phase out rate because of the increased amount of *Legacy Systems* compared to *Upgraded Legacy Systems,* and the second is that Upgraded Legacy Systems stock is fed only by the Upgrade Rate which is much smaller than the Maturation rate and therefore there is a much smaller number of Upgraded Legacy Systems whose phase-outs can be made more gradually over time.

For the practitioner this is important because that means that another factor, either the amount of *Needed Systems*, or the *System Maintenance Support Index,* and not just the lifetime of the system determines the rate at which the systems will be phased out.

Researchers should find interesting is that in three out of four system lifetime experiments the data converges to the same or nearly the same value at the end of the time scale. This means that there is a tendency of the model to settle in to an equilibrium state and resist changes regardless of the input. However the experiment that does not exhibit this is the effect of *Maximum Legacy System Lifetime* on *Phase Out Rate* whose data curves disperse instead of converge. This is important because it shows that even though the equations are structured the same for both the *Phase Out Rate* and the *Upgraded Phase Out Rate,* the model is capturing some of the dynamic relationships between other factors in the model, illustrating the validity of a System Dynamics model for this kind of supply chain.

Supply Base Experiment Discussion

The results from these experiments may have more importance for the researchers than for practitioners. This is because the supply base may be out of the realm of control for system administrators, yet they should be aware of these findings because the impact the supply base exerts on their systems.

All of the results from the four experiments show that equilibrium is reached by the end of the time scale and in some cases as soon as 40 time steps [see figs. 15, 17]. In the short run each experiment shows an initial correction in the model followed by a trend towards a certain value or close range of values, no matter what the input is according to the independent variable whether it be the *SM Capacity Adjustment Time* or the *NS Capacity Adjustment Time*. This is important for researchers because what is occuring is that the supply base could be dictating the level of this equilibrium; meaning that within the supply chain certain factors within the realm of control for the system administrator can influence the performance of that supply chain slightly, but that the performance is largely dependent on factors outside of that realm. This can be seen in the fact that the supply base affects the performance of the systems entering the system chain by way of *Current Systems* and exiting the system chain by way of the phase-out rates.

This is a very fertile area for additional research and practitioners also should be aware of this as it behooves them to do as much as they can to extend their range of influence and thereby have a larger degree of control over the supply chain.

In closing, all the experiments yielded interesting and significant results for both researchers and practitioners. The practitioners have gained valuable insights into the extent of their control over the lifetime and performance of their system chain, and the researched have gained insights into the viability of an SD model to model this kind of supply chain, as well as how the model stabilizes around certain performance factors as well as seek out an equilibrium point to keep that stability firm.

CHAPTER VII

CONCLUSION

This researched conducted a study into the feasibility of building a system dynamics (SD) model that could illustrate the effects of diminishing manufacturing sources on legacy systems. This was accomplished through a literature search and through testimony with three experts; two in the field of supply chain management, and one expert in the field of system dynamics. Once sufficient knowledge and data was obtained, the model was built using the VenSim software package and appropriate independent / dependent variable combinations were chosen to run experiments on. The experiments yielded results that illustrated the impact of independent variables on dependent variables and at what point about along a time scale they occurred. The results were then analyzed and the importance for both practitioners and researchers were obtained.

In the long run, 50 years in these experiments, most of the data converge to nearly the same value, i.e. they converge until an equilibrium is established based on the inputs to the system. However there are differences over those time spans and the data does vary during the experiments. The importance of these results from a managerial perspective tell us that certain variables that may have large effects in the short run do not always carry over these effects in the long run. Hence it is more appropriate to consider the changing of these variables as a solution if the problem needs to be solved quickly as the system chain will adjust quickly and then trend toward equilibrium. Of other importance are the experiments where the independent variable seemed to have little or no impact on the dependent variable. These variable pairs were chosen because of their assumed impact either discussed in research or through expert testimony and it is interesting to note that the results show otherwise.

From a research perspective the results point at interesting things for further research. The results showed the tendency for most variables to converge to some sort of equilibrium and few did not. The explanation behind this reaction could be of importance to research in better understanding the dynamics behind the system. Also of interest for researchers is the general tendency of the model to seek out an equilibrium and where the drive for this phenomenon comes from, i.e. does it come from the Stock Management Structure, the Supply Base, the factors that affect the Supply Base, or any combination of the above. A better understanding of this could yield important information leading to a better understanding of the largest influencing factors on a supply chain.

However there is a need to acknowledge the limitations in this research. The limitations stem from the testimony of the experts and the scope of the problem. The testimony of the experts was vast and useful however it was from a practitioner's point of view. Both of the experts work for the military and the supply chains they described are military supply chains that in most respects were very similar to commercial supply chains, yet nonetheless are still military supply chains. Also the variables and relationships were emphasized that were most important to their supply chains. The data gleaned from the testimony of the experts then skews the model more to the point of few of practitioners who deal with supply chains in the field and not the point of few of researchers. The scope of the problem also limits the research in that it was difficult to obtain real data that illustrated the effects of Diminishing Manufacturing Sources on Legacy Systems. In that regard it was unfeasible to compare the results obtained from the experiments with real world data trends and compare them side-by-side. The lack of data also made writing specific equations that modeled the impact of one variable upon another very difficult; therefore simpler equations had to be written that could model the impact of one variable upon another based on the testimony of the experts. These two limitations mean that the results follow closely to sensitivity analysis type results that matter most to practitioners in that they model the amount of impact one variable has upon another and not specific trend modeling. Hence this is an initial study looking at this very important area.

Future research should further investigate these critical aspects particularly these things that lead us to curious results. Also further research should attempt to apply this model, or a similar model, to different types of supply chains both military and commercial where basic initial information can be obtained to run appropriate studies and comparing the results to those supply chains as well. Additionally the further application of SD as a modeling tool for legacy system supply chains should be investigated by upgrading the model with more specific data and equations in an attempt to determine the feasibility of using such an SD model to accurately predict and or follow real world trends in legacy system supply chain risk management.

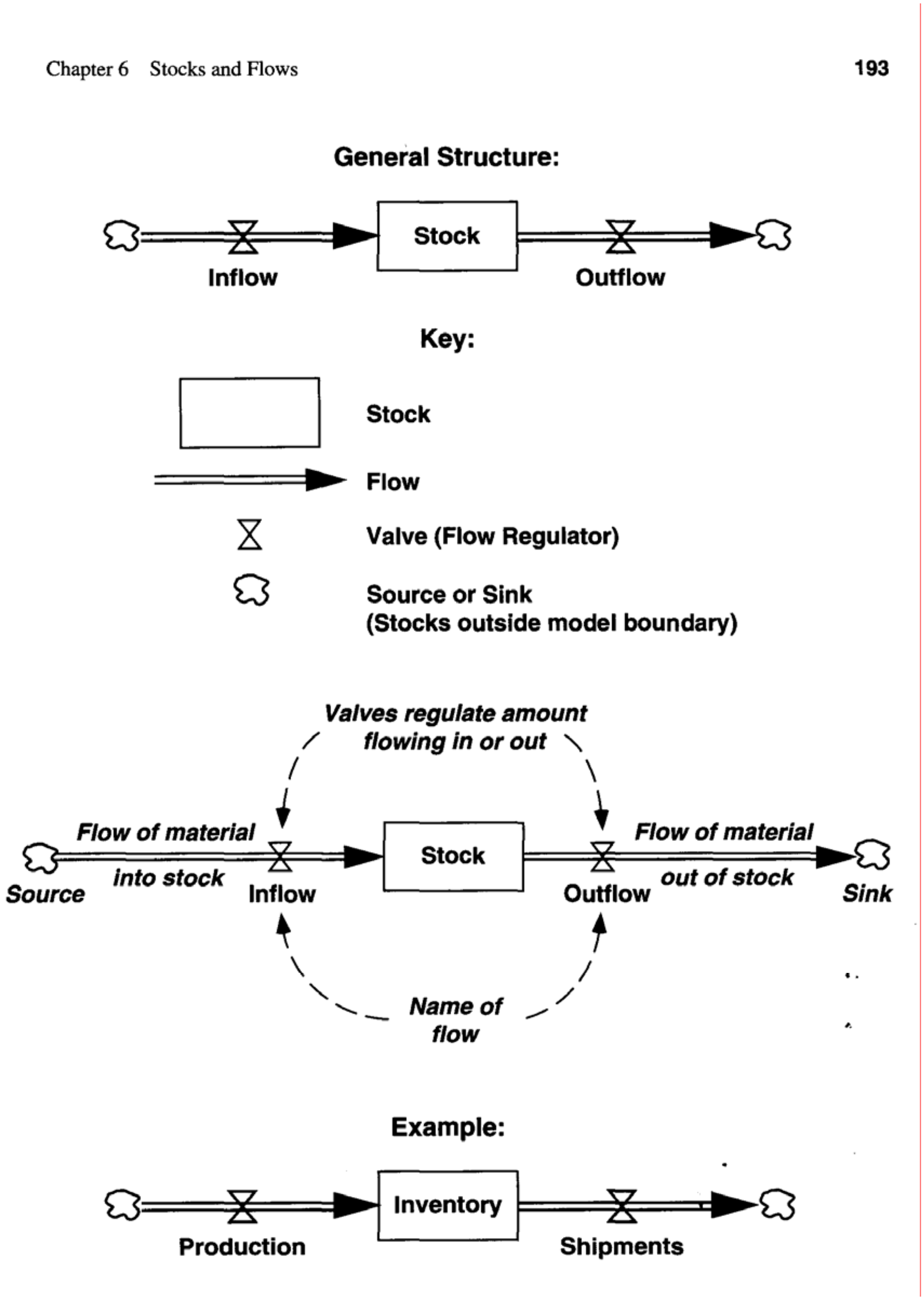


Figure 1: Introduction to Notation [Sterman 2000]

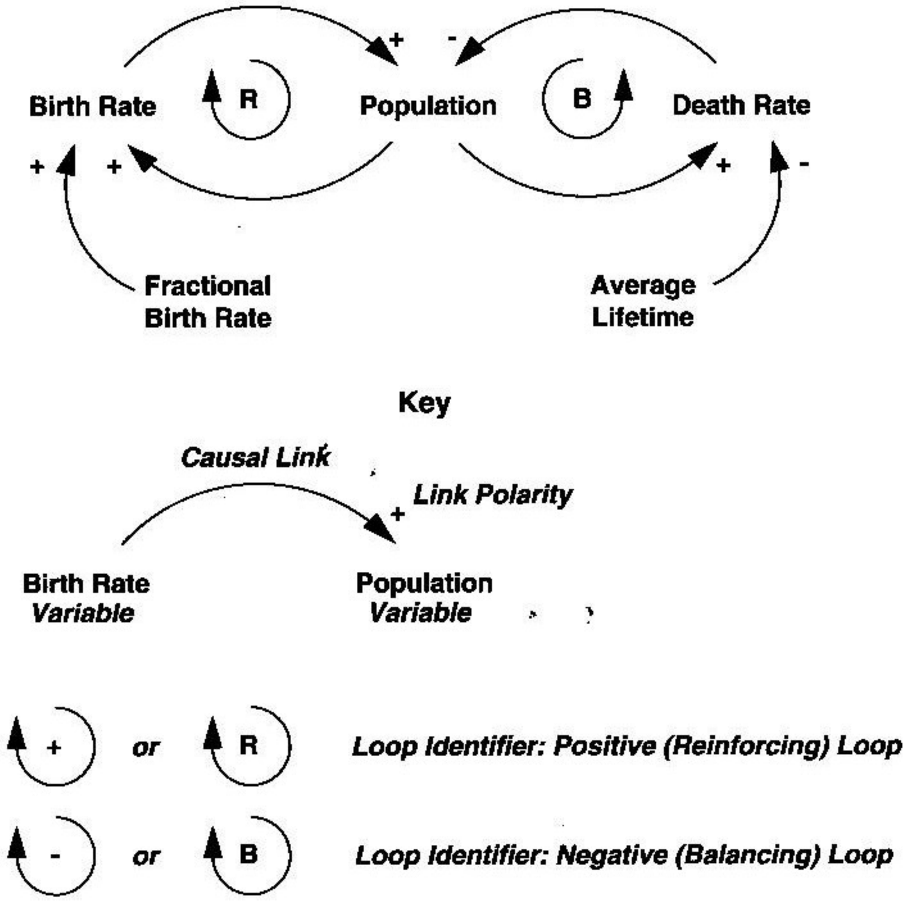
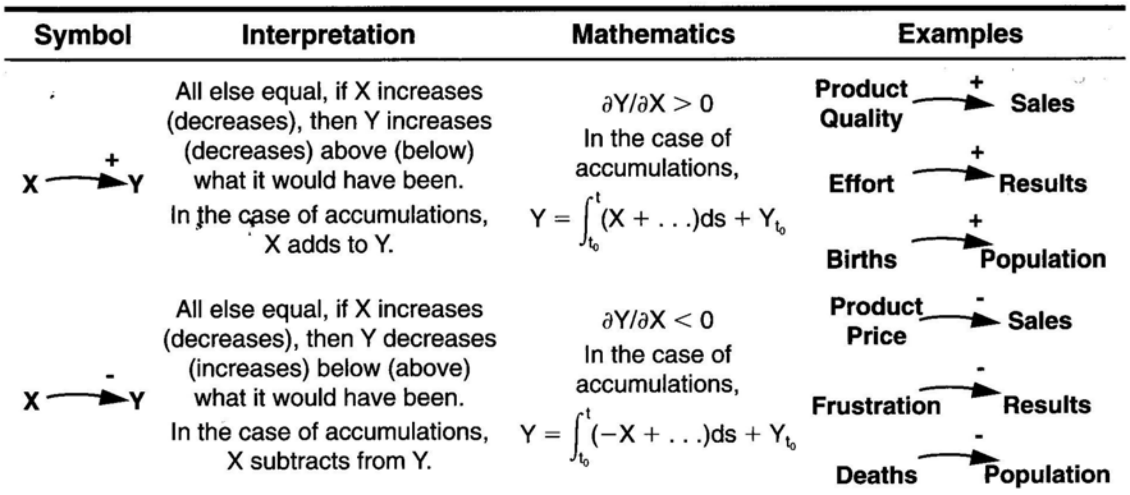


Figure 2: Causal Loop Diagram Notation [Sterman 2000]

Table 1: Link Polarity: Definitions and Examples [Sterman 2000]



Symbol	Interpretation	Mathematics	Examples
$X \xrightarrow{+} Y$	All else equal, if X increases (decreases), then Y increases (decreases) above (below) what it would have been. In the case of accumulations, X adds to Y.	$\partial Y/\partial X > 0$ In the case of accumulations, $Y = \int_{t_0}^{t}(X + \ldots)ds + Y_{t_0}$	Product Quality $\xrightarrow{+}$ Sales Effort $\xrightarrow{+}$ Results Births $\xrightarrow{+}$ Population
$X \xrightarrow{-} Y$	All else equal, if X increases (decreases), then Y decreases (increases) below (above) what it would have been. In the case of accumulations, X subtracts from Y.	$\partial Y/\partial X < 0$ In the case of accumulations, $Y = \int_{t_0}^{t}(-X + \ldots)ds + Y_{t_0}$	Product Price $\xrightarrow{-}$ Sales Frustration $\xrightarrow{-}$ Results Deaths $\xrightarrow{-}$ Population

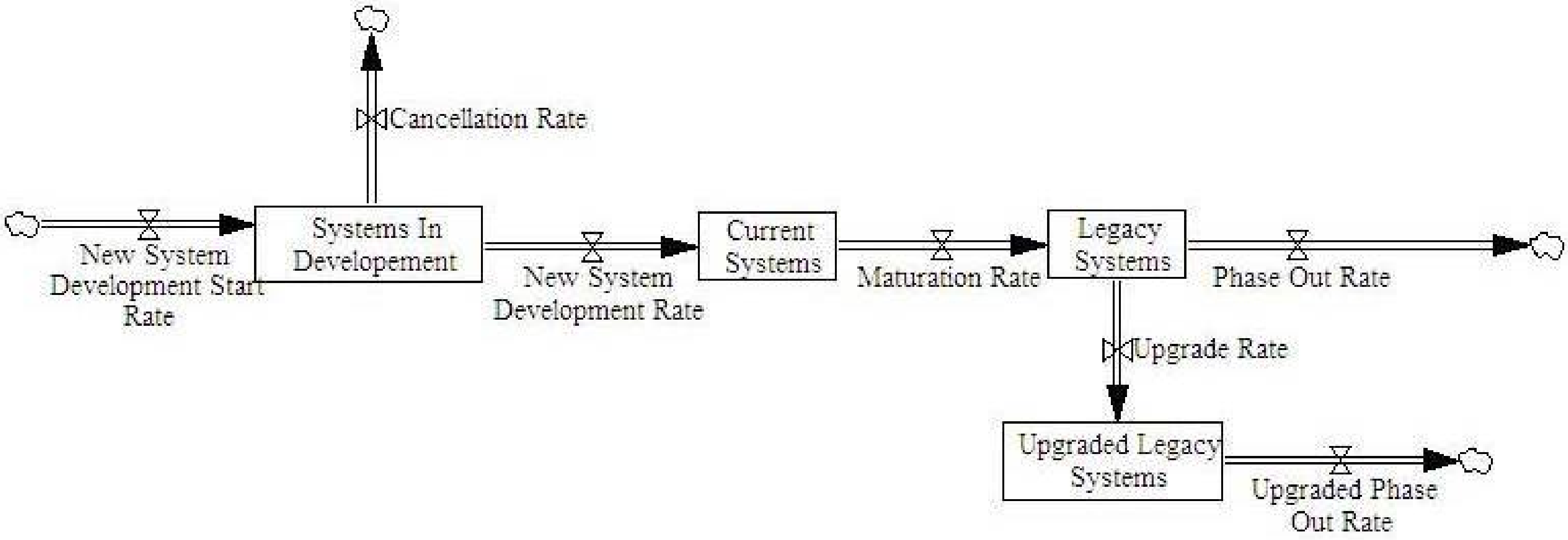


Figure 3: System Chain

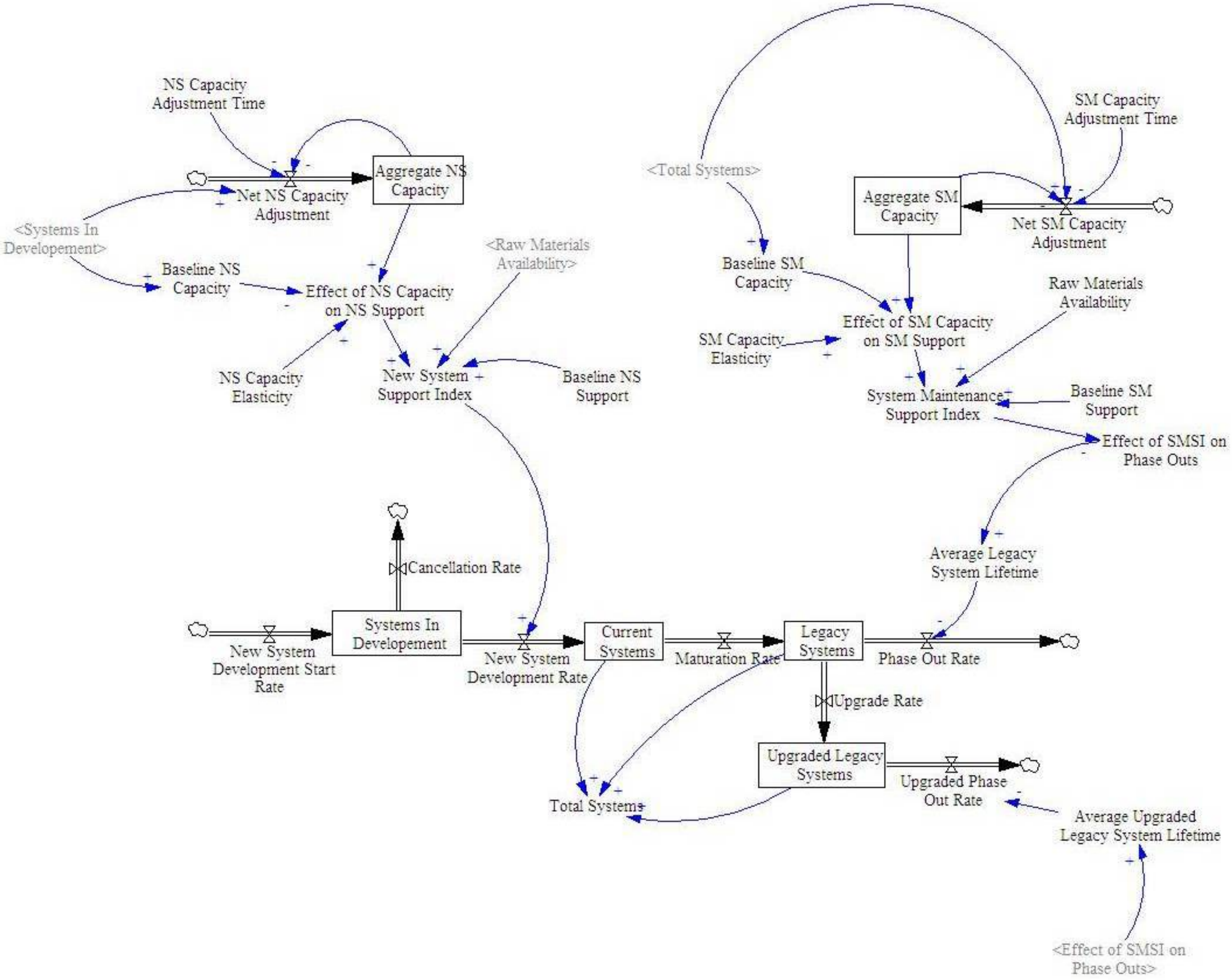


Figure 4: Supply Base

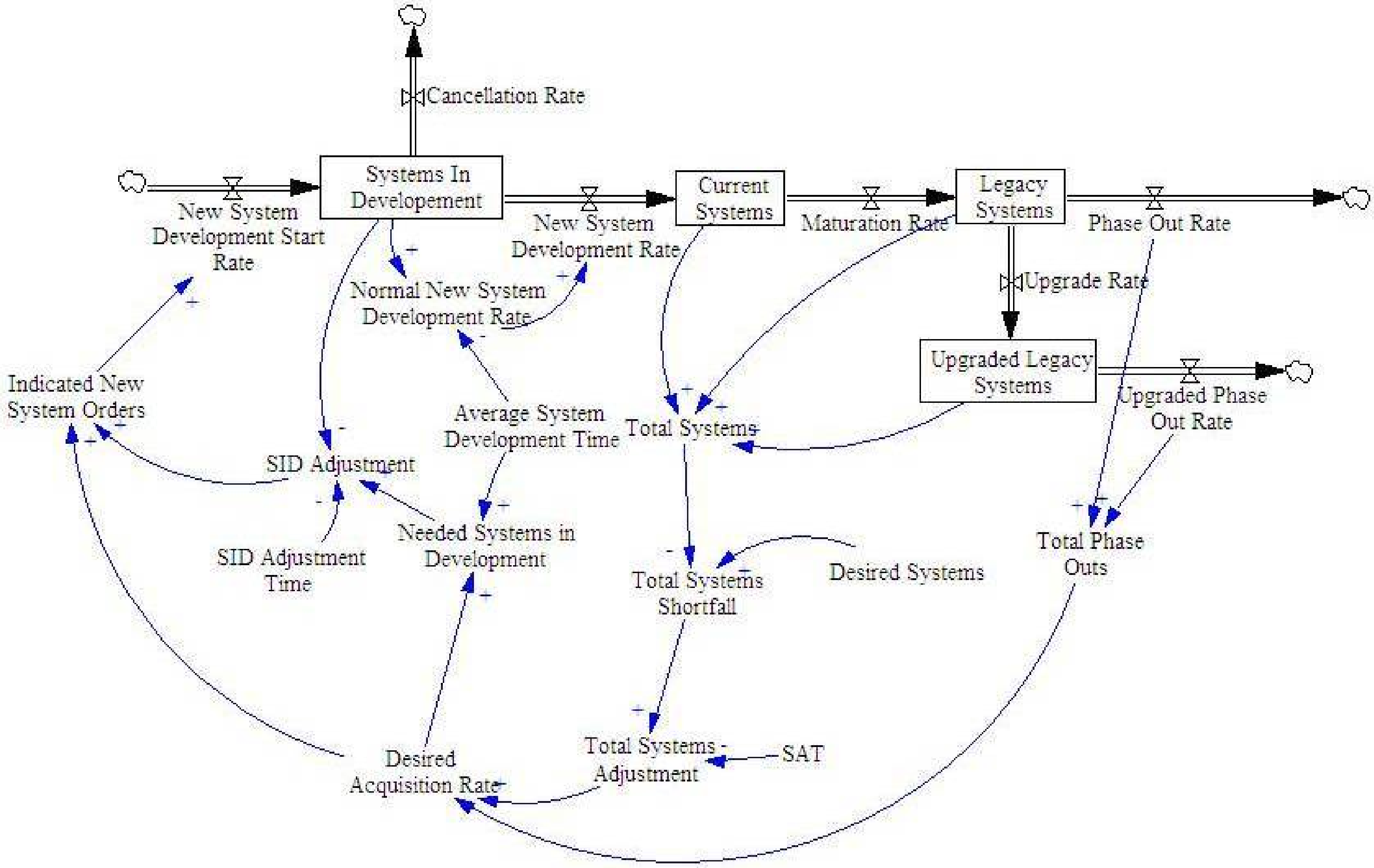


Figure 5: Stock Management Structure

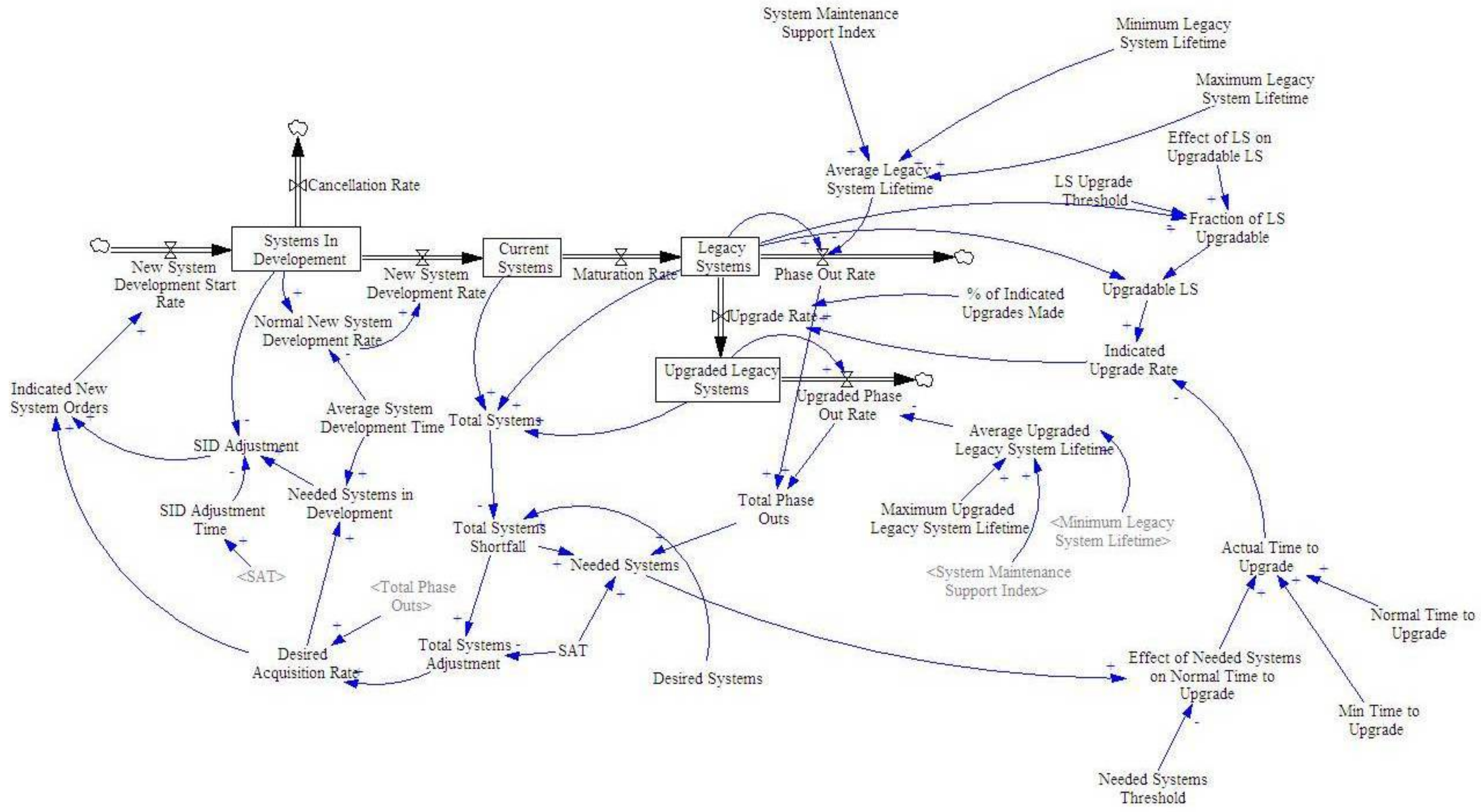


Figure 6: The Upgrade Structure

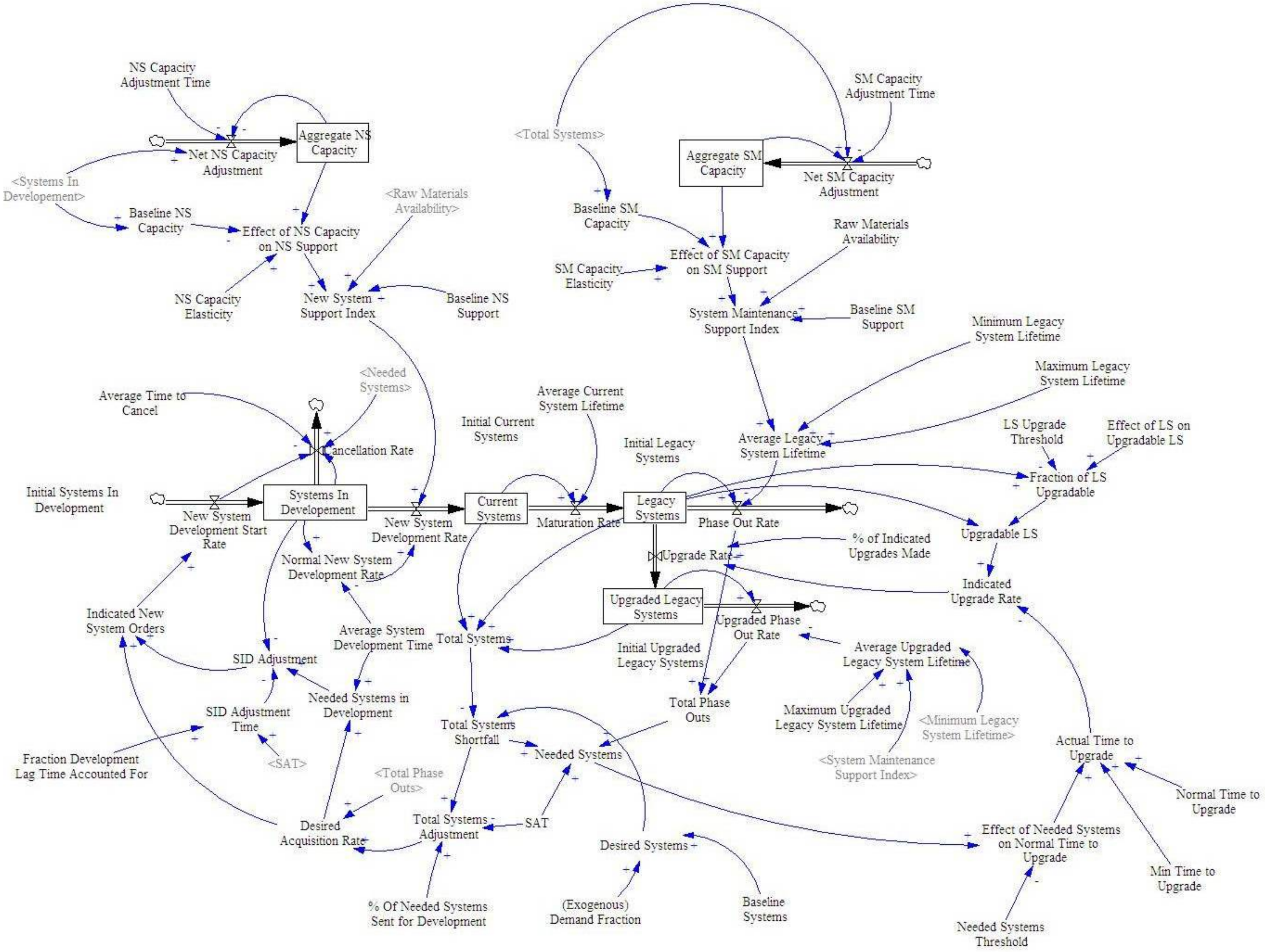


Figure 7: The Complete Model

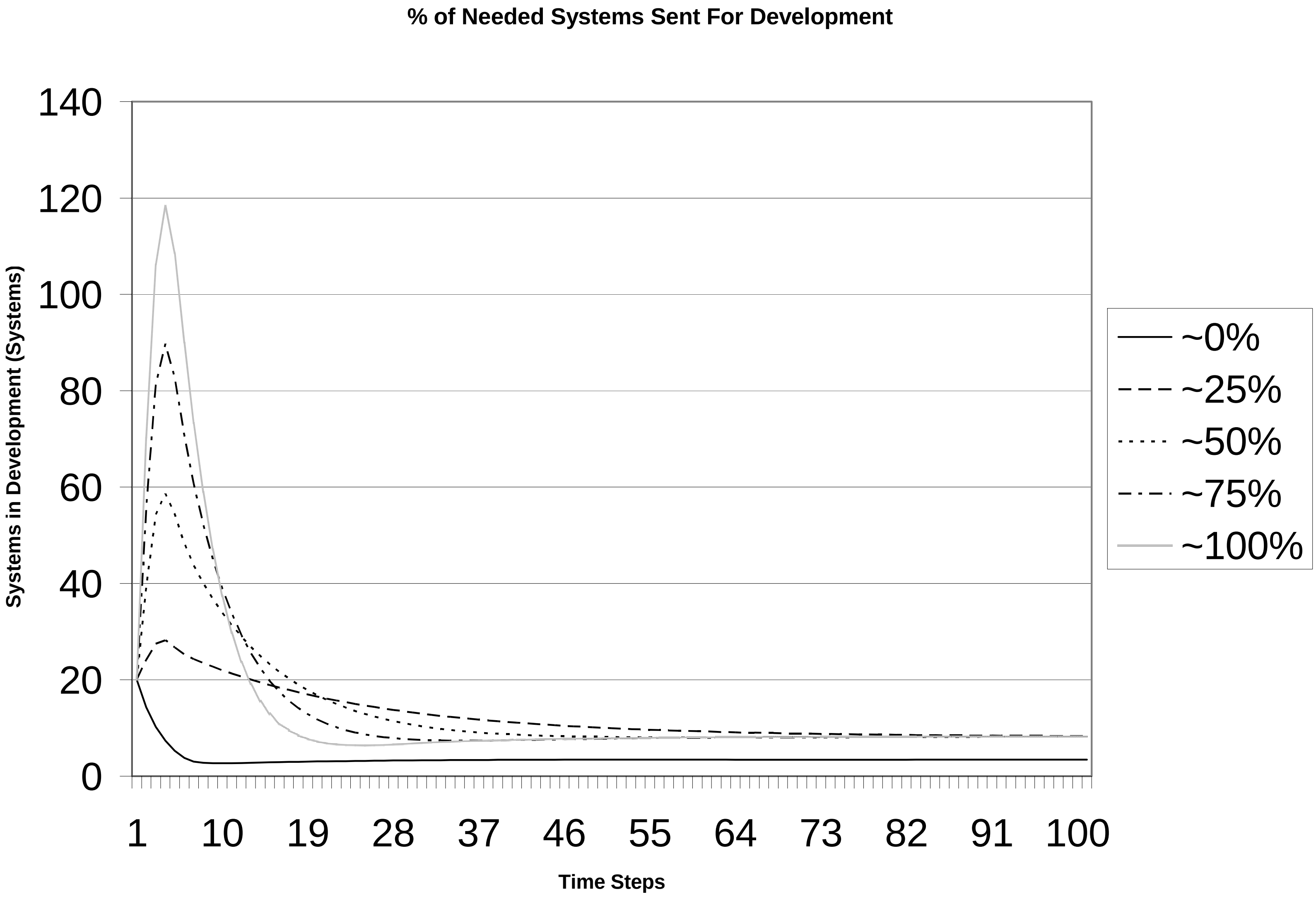


Figure 8: The Effect of *% of Needed Systems Sent For Development* on *Systems In Development*

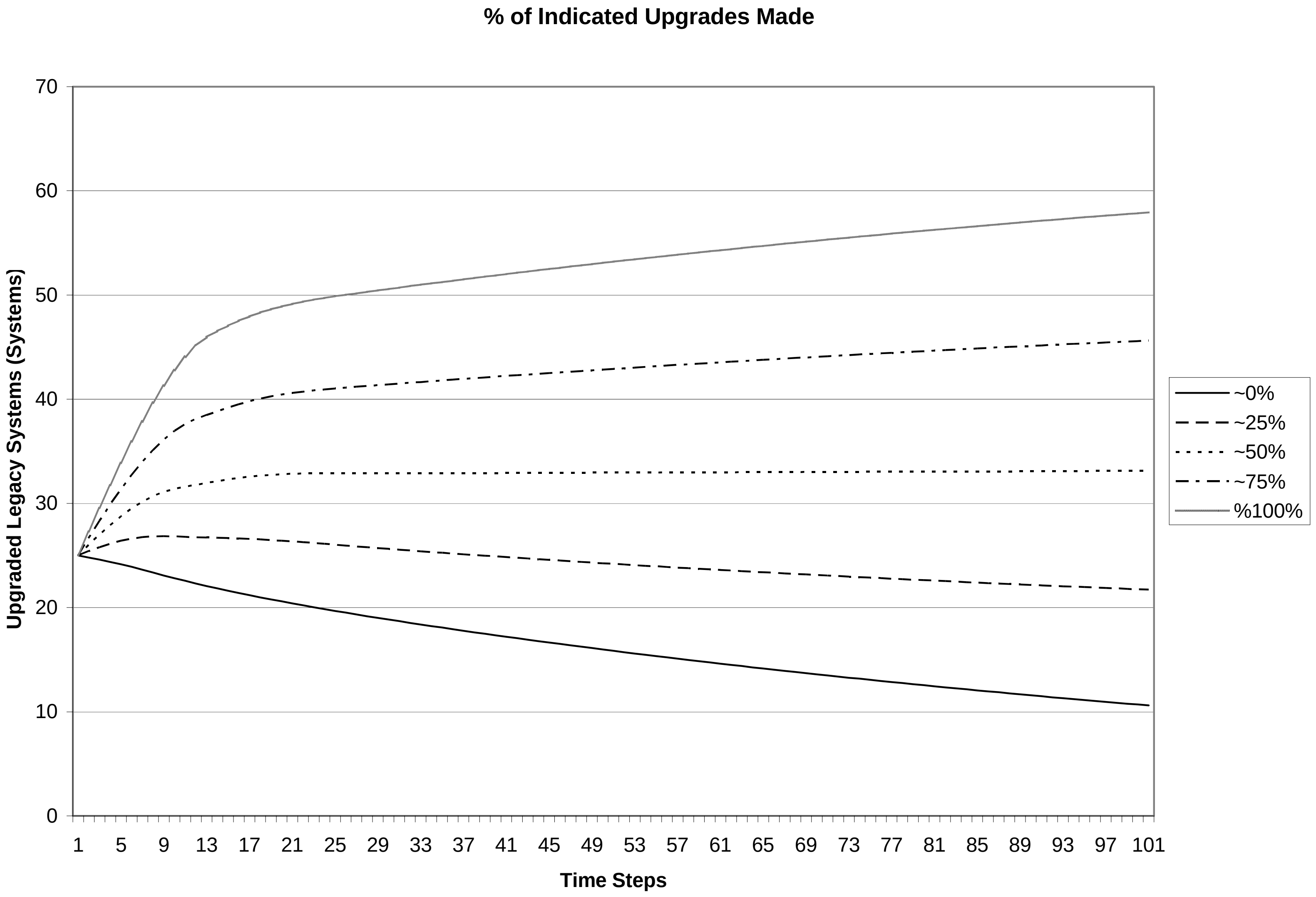


Figure 09: Effect of *% of Indicated Upgrades Made* on *Upgraded Legacy Systems*

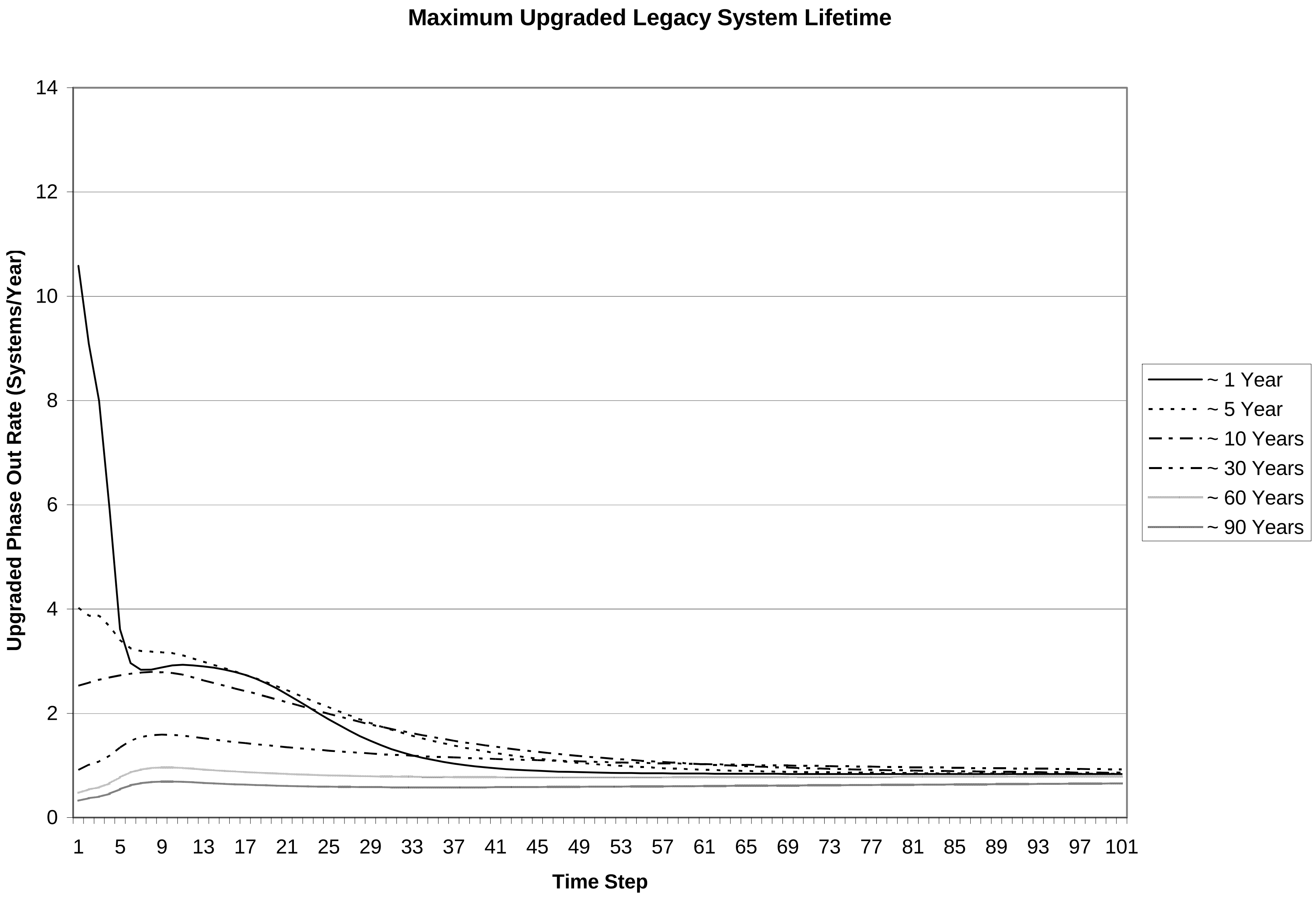


Figure 10: Effect of *Maximum Upgraded Legacy System Lifetime* vs. *Upgraded Phase Out Rate*

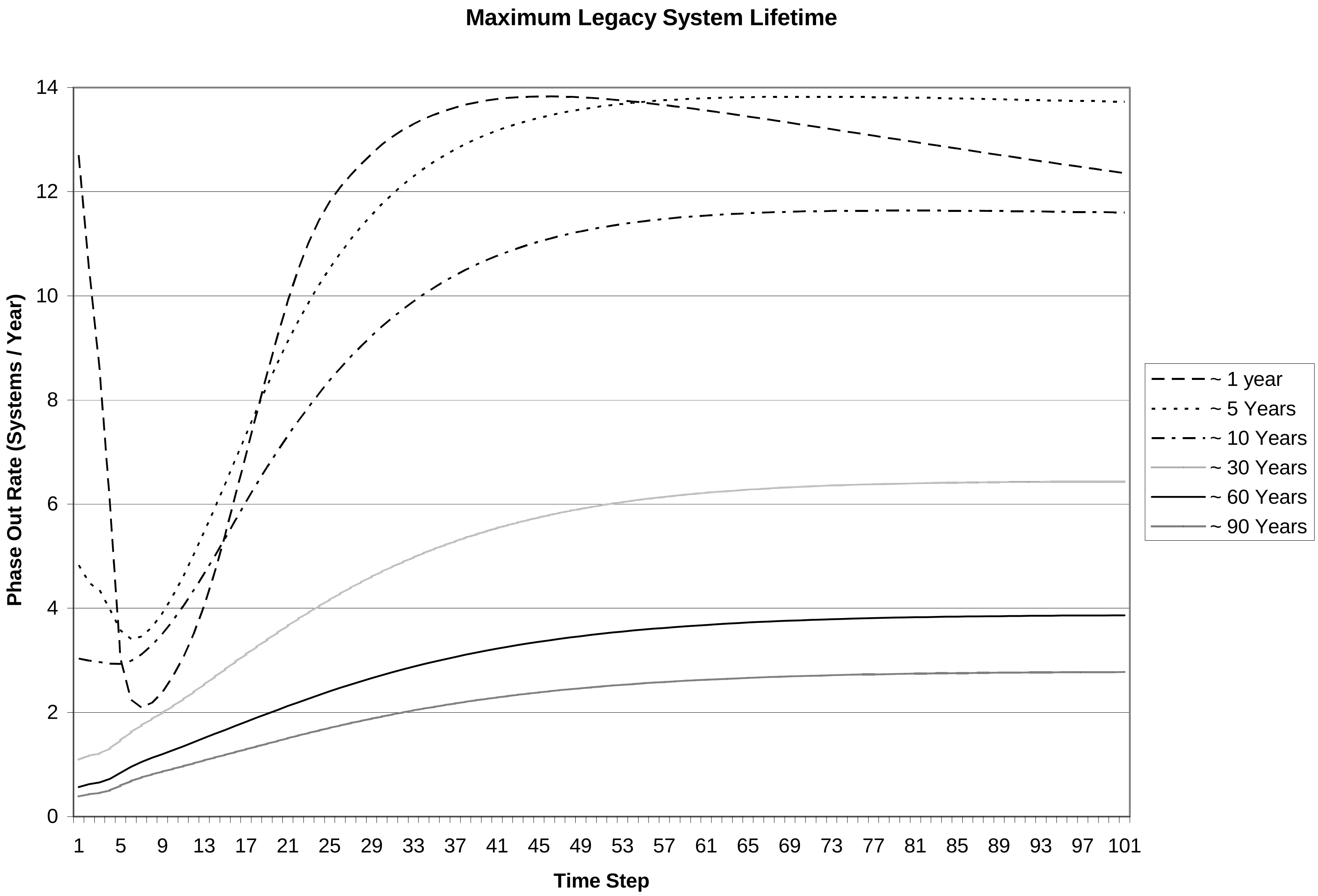


Figure 11: The Effect of *Maximum Legacy System Lifetime* on *Phase Out Rate*

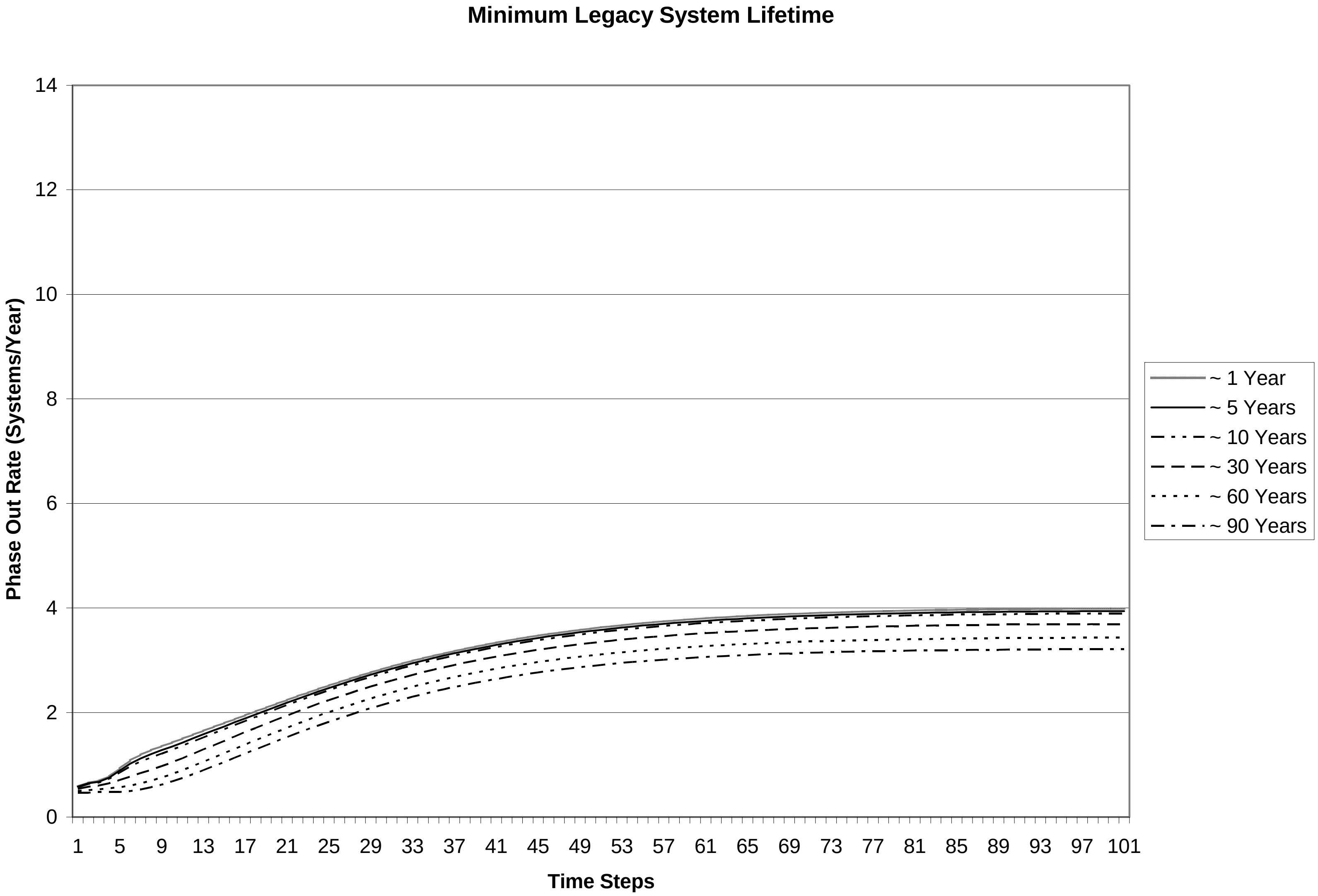


Figure 12: The Effect of *Minimum Legacy System Lifetime* on *Phase Out Rate*

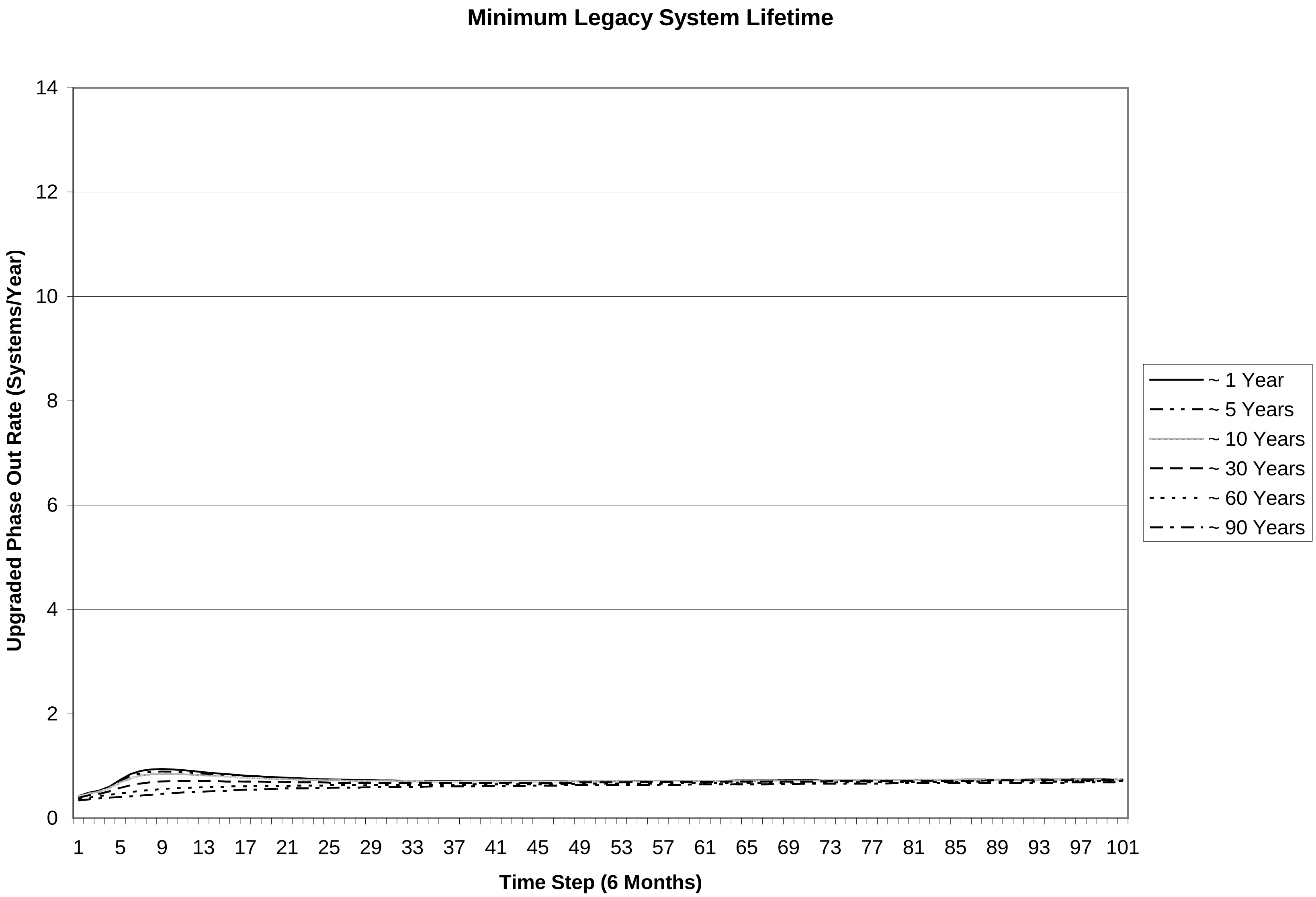


Figure 13: The Effect of *Minimum Legacy System Lifetime* on *Upgraded Phase Out Rate*

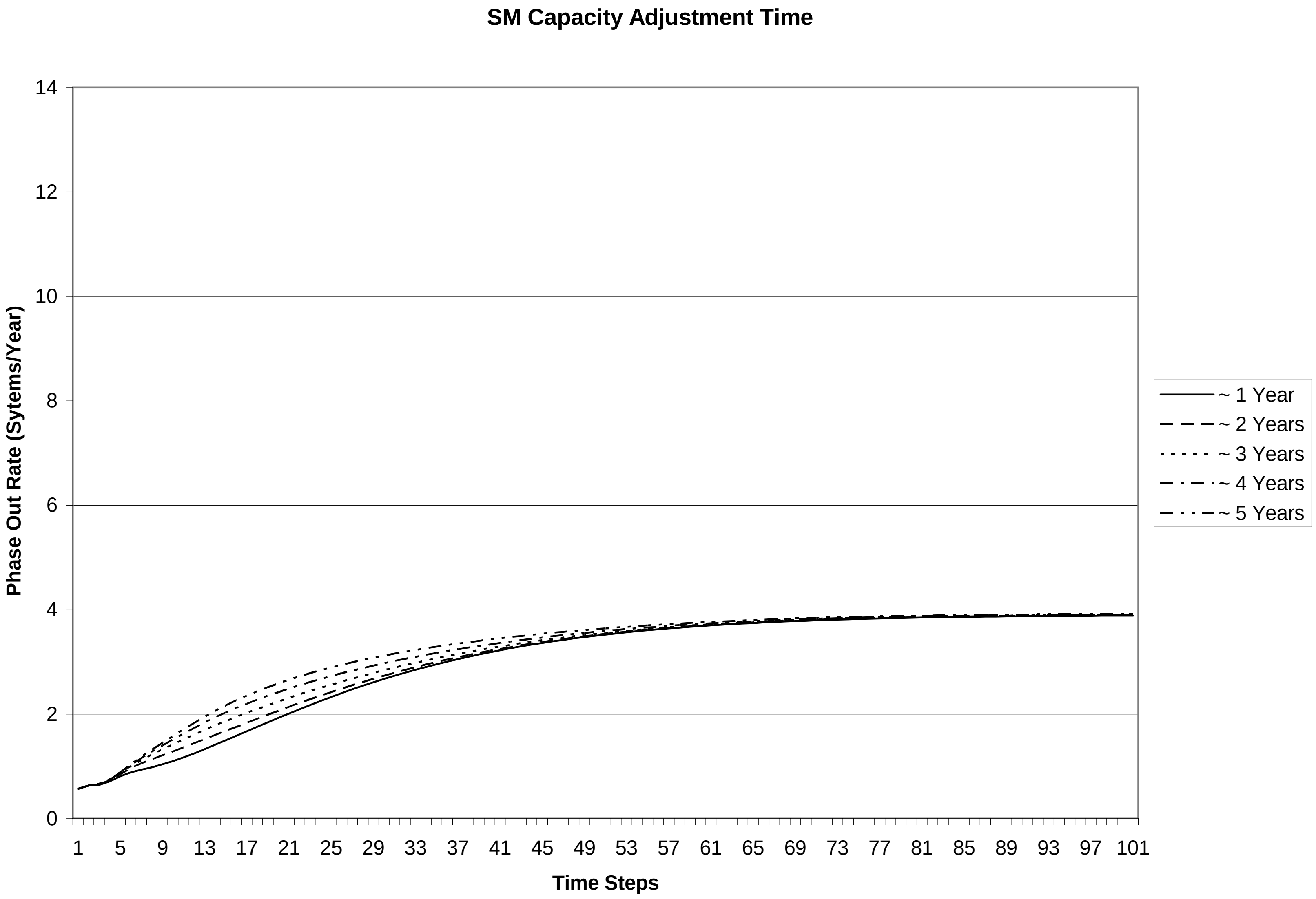


Figure 14: The Effect of *SM Capacity Adjustment Time* on *Phase Out Rate*

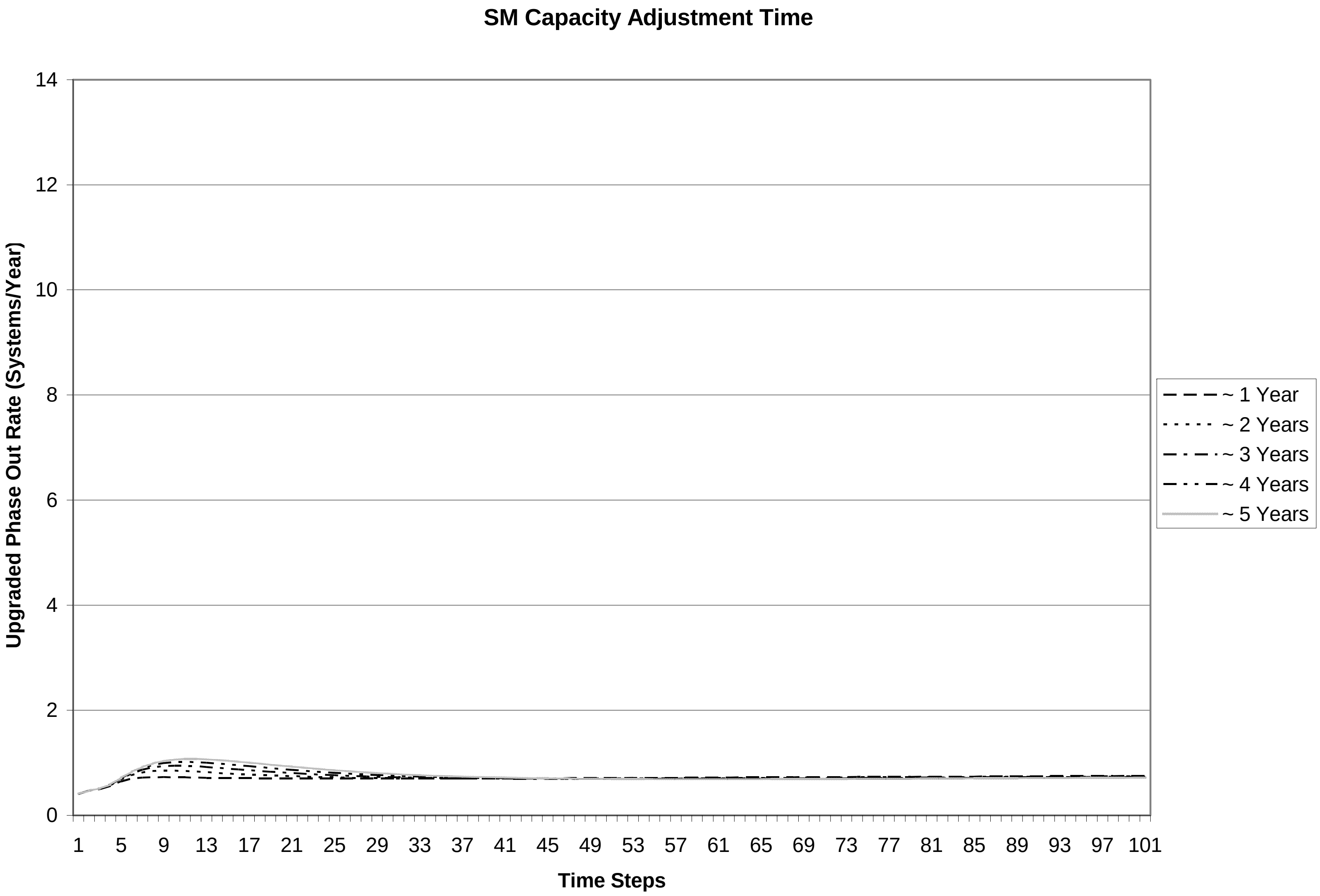


Figure 15: The Effect of *SM Capacity Adjustment Time* on *Upgraded Phase Out Rate*

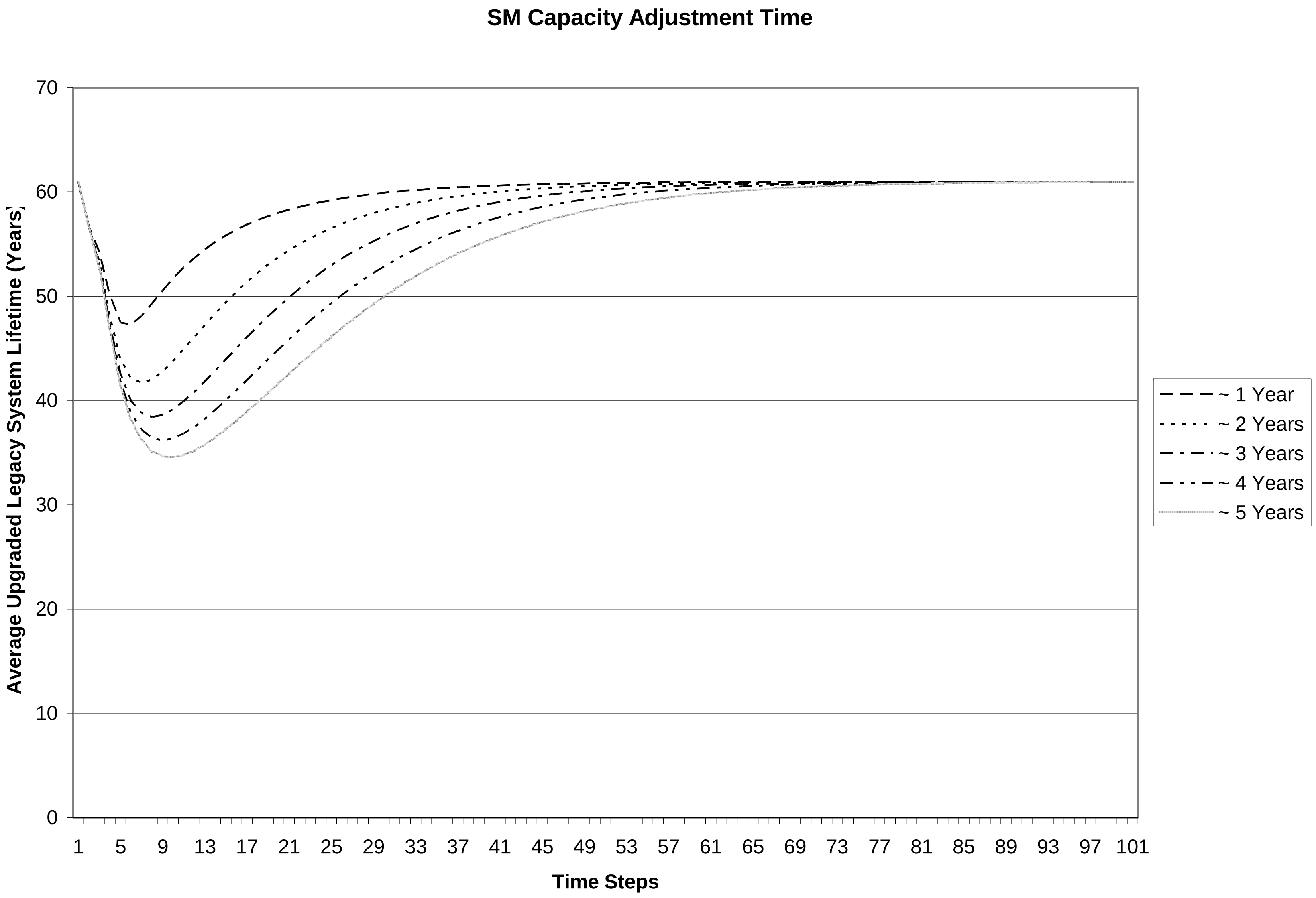


Figure 16: The Effect of *SM Capacity Adjustment Time* vs. *Average Upgraded Legacy System Lifetime*

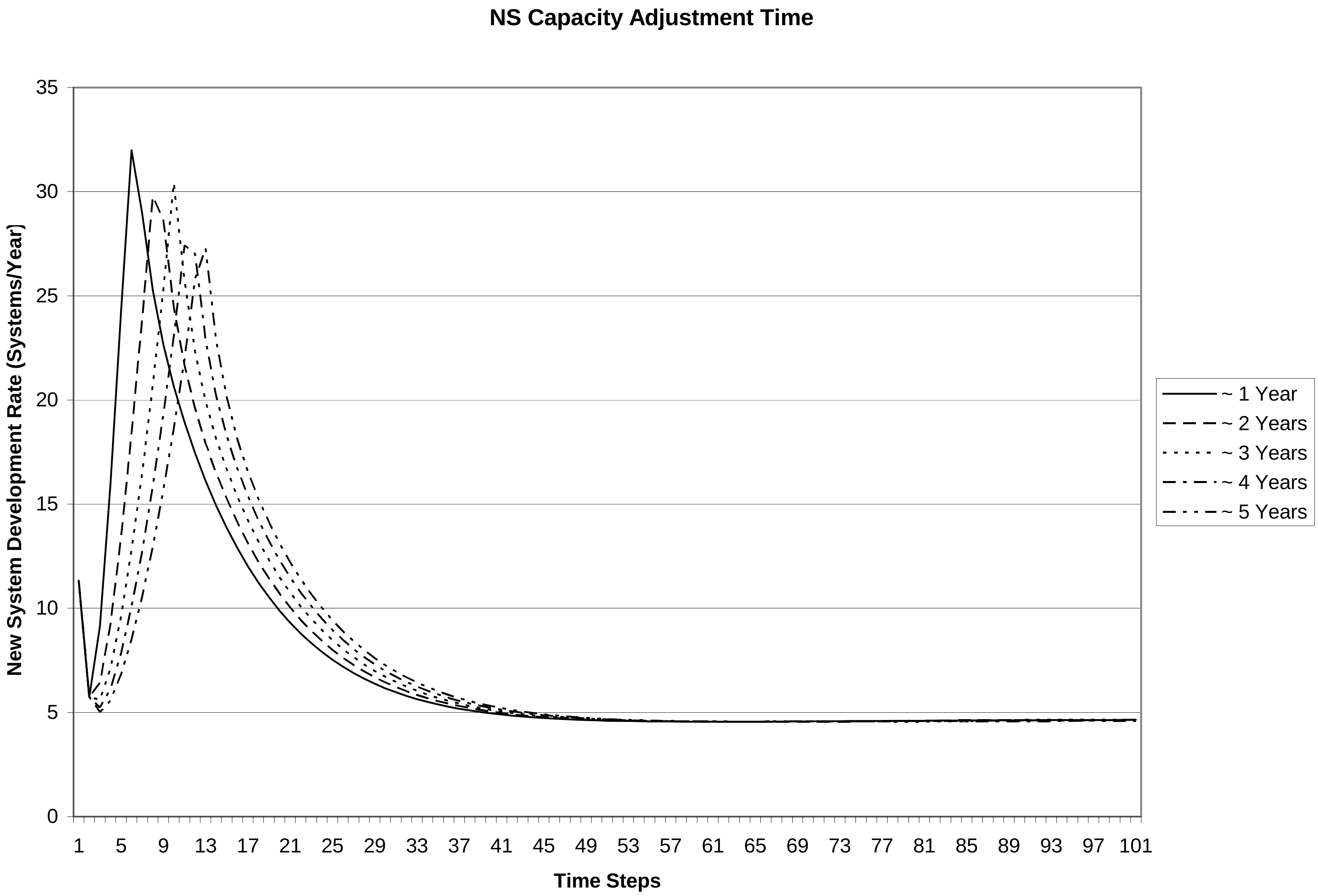


Figure 17: The Effect of *NS Capacity Adjustment Time* on *New System Development Rate*

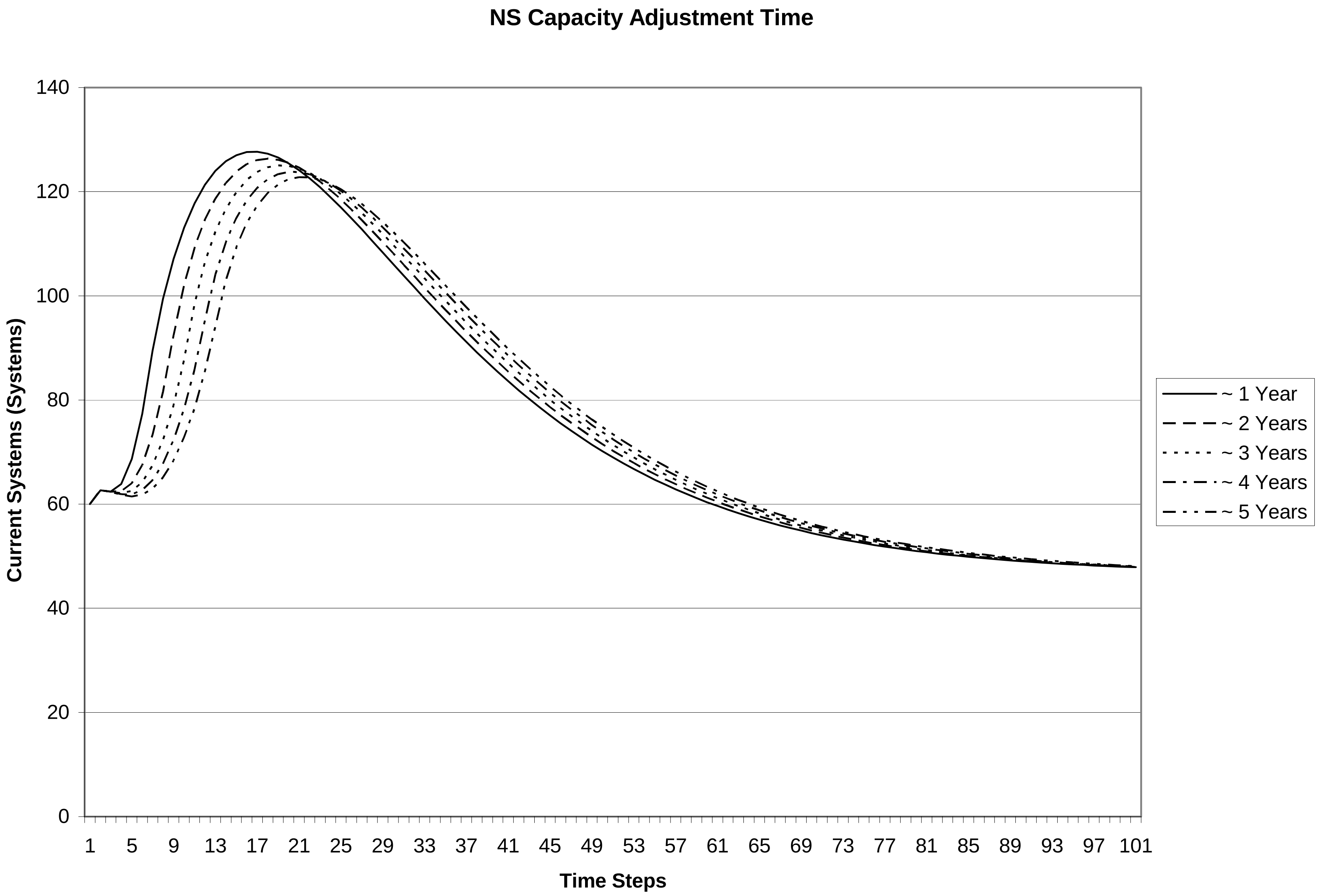


Figure 18: The Effect of *NS Capacity Adjustment Time* on *Current Systems*

Table 02: Managerial Experiments

Managerial Experiments			
Independent Variable	**Dependent Variable**	**Values**	**Results**
% of Needed Systems Sent for Development	Systems in Development	0-100%	Initial large correction within the first 20 time steps followed by a convergence of all data (except 0% curve) to the same value; showing that no matter how many systems are sent for development, in the end the system finds equilibrium.
% of Indicated Upgrades Made	Upgraded Legacy Systems	0-100%	Initial correction within the first 12 time steps then the curves follow a fixed slope and disperse to different values ranging from 11 to 58 Upgraded Legacy Systems showing a disparity between the upgrade rate and the phase out rate.

Table 03: Legacy System Lifetime Experiments

Legacy System Lifetime Experiments			
Independent Variable	**Dependent Variable**	**Values**	**Results**
Maximum Upgraded Legacy System Lifetime	Upgraded Phase Out Rate	0-90 Time Steps	As the maximum lifetime decreases a drastic correction is made within the first 7 time steps, then the curves begin to level out and converge upon nearly the same value at the end. This shows that the maximum lifetime of a legacy system has a much larger
Maximum Legacy System Lifetime	Phase Out Rate	0-90 Time Steps	As the maximum lifetime decreases a drastic correction is also seen here within the 7 time steps. However afterwards instead of converging to approximately the same value the curves disperse to indicate a wide range of phase out rates. This shows that m
Minimum Legacy System Lifetime	Phase Out Rate	0-90 Time Steps	The curves in this experiment all follow the same shape. The phase out rates gradually increase and then level off at a value in between approximately 3.25 and 4.0 systems per year. This shows that minimum legacy system lifetime does not have that large
Minimum Legacy System Lifetime	Upgraded Phase Out Rate	0-90 Time Steps	Within the first 20 time steps the data curves fluctuate heavily and then level out converging in the end to a range of 0.68 and 0.75 systems per year. This shows that the minimum legacy system lifetime has a greater impact on upgraded phase out rate ear

Table 04: Supply Base Experiments

Supply Base Experiments			
Independent Variable	**Dependent Variable**	**Values**	**Results**
SM Capacity Adjustment Time	Phase Out Rate	0-5 Time Steps	The SM Capacity adjustment time has little impact on the Phase out Rate as seen in the graph. The curves follow the same shape, the difference being within the first 40 time steps where the slope is steeper as the adjustment time increases. Eventually t
SM Capacity Adjustment Time	Upgraded Phase Out Rate	0-5 Time Steps	The data shows that once again the SM Capacity Adjustment Time has a larger significance in the beginning of the time frame. The curves show a large correction within the first 40 time steps and then eventually converge to nearly the same value indicated
NS Capacity Adjustment Time	New System Development Rate	0-5 Time Steps	The NS Capacity Adjustment Time has a large impact on New System Development Rate within the first 40 time steps. This is seen by a large correction to increase the development rate within 20 time steps and then another correction to lower the developmen
NS Capacity Adjustment Time	Current Systems	0-5 Time Steps	The NS Capacity Adjustment Time has a larger significance within 30 time steps and the number of Current Systems increases sooner with a decreased adjustment time. However in the long run the data converges to the same point indicating that eventually eq

REFERENCES

Akkermans, Henk. (1995) “Developing a logistics strategy through participative business modelling.” International Journal of Operations & Production Management, 15(11):100-112

Akkermans, Henk; Bogerd, Paul. (1999) “Virtuous and vicious cycles on the road towards international supply chain management.” International Journal of Operations & Production Management, 19(5/6):565-581

Akkermans, H. (2001) “Emergent supply networks: system dynamics simulation of adaptive supply agents” System Sciences. Proceedings of the 34th Annual Hawaii International Conference,

Alkhatib, G. (1992) “The maintenance problem of application software: an empirical analysis” 1 Sofm. Maint., Res. Pract., 4(2): 83-104

An, L.; Jeng, J.J.; Ettl, M.; Chung, J.-Y. (2004) “A system dynamics framework for sense-and-respond systems” IEEE International Conferene on E-Commerce Technology for Dynamic E-Business. 6 – 13

Anderson, E. G. JR.; Fine, C. H.; and Parker, G. G. (1996) “Upstream volatility in supply chain: the machine tool industry as a case study.” Working papers, MIT Sloan School of Management, Cambridge, MA.

Angerhofer, B.J.; Angelides, M.C. (2000) “System dynamics modelling in supply chain management: research review” Simulation Conference Proceedings, 1:342 - 351

Bennett, K. (1995) “Legacy systems: coping with stress” IEEE Software, 12(1):19 - 23

Bennett, K.H.; Ramage, M.; Munro, M. (1999) “Decision model for legacy systems” IEEE Proceedings on Software, 146(3):153 – 159

Bhushi, U.M.; Javalagi, C.M. (2004) “System dynamics application to supply chain management: a review” IEEE International Conference on Engineering Management, 3:1244 - 1248

Bisbal, J.; Lawless, D.; Bing Wu; Grimson, J. (1999) “Legacy information systems: issues and directions” IEEE Software, 16(5):103 – 111

Bowers, Peter M. (1989) Boeing Aircraft Since 1916 Annapolis, MD:Naval Institute Press.

Bozarth, Cecil C.; Handfield, Robert B. (2005) “Introduction to Operations and Supply Chain Management” 1st. Ed. Pearson Prentice Hall

Burgess, Thomas F. (1998) “Modelling the impact of reengineering with system dynamics” International Journal of Operations & Production Management, 18(9/10):950-963

Clark, K.P. (2002) “Flight hardware delivery breakthroughs via engineering / business best-practices synthesis” IEEE Conference Proceedings on Aerospace, 7:3409-3428

Computer (1999) “Bracing for the millennium” 32, (1):51 – 56

Computerworld (2003) “Support Ends for Windows NT 4.0 Workstation” July 07; accessed 3/7/2006 http://www.computerworld.com/printthis/2003/0,4814,82772,00.html

Condra, L.W.; Anissipour, A.A.; Mayfield, D.D.; Pecht, M.G. (1997) “Electronic Components Obsolescence**”**, IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part A, 20(3):368 - 371

Connors, Timothy J. (2005) “Managing obsolescence takes commitment to 'best practices'” Military & Aerospace Electronics, 16(8):9-10

De Lucia, A.; Fasolino, A.R.; Pompelle, E. (2001) “A decisional framework for legacy system management” IEEE International Proceedings on Software Maintenance. :642 – 651

Del Vecchio, A.; Towill, D. R. (1990) “Conceptual modelling of industrial production distribution system via standard form.” Mathematical and Computer Modelling, 14:1029 - 1034.

Drake, M. (2003) “Sharing obsolescence information at Raytheon with the component obsolescence and reuse tool” Reliability and Maintainability Symposium. :277 - 279

Evans, G.N.; Towill, D.R.; Naim, M.M. (1995) “Business process re-engineering the supply chain.” Production Planning & Control, 6(3):227-237

Forrester, Jay W. (1961,1999) Industrial Dynamics, Cambridge, Mass. MIT Press

Gaonkar, R.; Viswanadham, N. (2003) “Robust supply chain design: a strategic approach for exception handling” IEEE Proceedings on Robotics and Automation, 2:1762 - 1767

Gaonkar, R.; Viswanadhani, N. (2003) “Supply chain planning over product lifecycles” IEEE Proceedings on Intelligent Robots and Systems, 3:2329 – 2334

Gupta, M. P.; Bhatia, D. (2005) “Reworking with a Legacy Financial Accounting System: Lessons from a Pharma Company” The Journal for Decision Makers, 30(3):79-92

Helo, P. T. (2000) “Dynamic modelling of surge effect and capacity limitation in supply chains.” International Journal of Production Research, 38(17):4521-4533

Houston, J.A.; Concha, L.; Bohannan, R. (1997) “VHDL design environment for legacy electronics (VDELE)” Proceedings on VHDL International Users' Forum, :162 - 169

Jeng, J.T. (2004) “Supply chain risk management” Semiconductor Manufacturing Technology Workshop, Proceedings:139–140

Jüttner, Uta. (2005) “Supply chain risk management.” International Journal of Logistics Management 16(1):120-141

Kerzner, Harold (2003) Project Management: A systems approach to planning, scheduling, and controlling 8th Edition John Wiley & Sons, Inc.; Hoboken, New Jersey

Kobren, Bill; Melnikow, Alex; Robinson, David G. (2005) “Mitigating Diminishing Manufacturing Sources and Material Shortages.” Defense & AT-L, 34(3):62-66

Lientz, B.; and Swanson, E.B. (1980) “Software maintenance management: a study of the maintenance of computer application software in 487 data processing organisations” Addison-Wesley, Reading, MA, USA, 1980

Lientz, B., Swanson, E.B., and Tompkins, G.E. (1978) ‘Characteristics of applications software maintenance’, Commun. ACM, 21(6):466-471

Littlejohn, K.; DelPrincipe, M.V.; Preston, J. D. (2000) “Embedded information system re-engineering” IEEE Aerospace and Electronics Magazine. 15(11):3-7

Madisetti, V.K.; Jung, Y.K.; Khan, M.H.; Kim, J.; Finnessy, T. (1999) “Reengineering legacy embedded systems” IEEE Design & Test of Computers, 16(2):38 – 47

Madisetti, V.; Jung, Y.K.; Khan, M.; Kim, J.; Finnessy, T. (2000) “On upgrading legacy electronics systems: methodology, enabling technologies and tools” Proceedings: VHDL International Users Forum Fall Workshop. :7-14

Mason-Jones, R.; Towill, D. R. (1999) “Total cycle time compression and the agile supply chain.” International Journal of Production Economics, 62:61 - 73.

Narasimha, K.B.; Roy, R. (2005) “Supply Chain Structure Design for a Short Lifecycle Product: A Loop Dominance Based Analysis” System Sciences. Proceedings:78a - 78a

Oyarbide, A.; Baines, T. S.; Kay, J. M.; Ladbrook, J. (2003) “Manufacturing Systems Modelling Using System Dynamics: Forming a Dedicated Modelling Tool” Journal of Advanced Manufacturing Systems, 2(1):71 – 87

Pai, R.R.; Kallepalli, V.R.; Caudill, R.J.; Meng, Chu Zhou (2003) “Methods toward supply chain risk analysis,” IEEE Transactions on Systems, Man and Cybernetics, 5:4560 - 4565

Pashov, I.; Riebisch, M.; Philippow, I. (2004) “Supporting architectural restructuring by analyzing feature models” Proceedings: Software Maintenance and Reengineering, 25 – 34

Pidd, M. (1993) Computer Simulation in Management Science, 3rd Edition. Chichester: John Wiley.

Puranek, H. V. D.; Savit, R.; Riolo, R. (1998) “Agent Based Modeling vs. Equation Based Modeling: A Case Study and User’ Guide.” Proceedings of Multi-Agent Productivity Press:3-28.

Rabelo, L.; Helal, M.; Lertpattarapong, C.; (2004) “Analysis of supply chains using system dynamics, neural nets, and eigenvalues” Simulation Conference. Proceedings, 2:1136 - 1144

Ransom, J.; Somerville, I.; Warren, I. (1998) “A method for assessing legacy systems for evolution” Proceedings: Software Maintenance and Reengineering, 128 – 134

Reid, R.A.; Koljonen, E.L. (1999) “Validating a manufacturing paradigm: a system dynamics modeling approach” Simulation Conference Proceedings 1:759 - 765

The RENAISSANCE ESPRIT Project (2005) “Renaissanceweb: The resource for software reengineering, maintenance, evolution, reuse, and reverse engineering” [Accessed 12/11/2005] http://www.comp.lancs.ac.uk/projects/renaissance

Riddalls, C. E.; Bennett, S.; Tipi, N. S. (2000) “Modelling the dynamics of supply chains.” International Journal of Systems Science, 31(8):969-976

Schieritz, N.; GroBler, A. (2003) “Emergent Structures in supply chains – a study integrating agent-based and system dynamics modeling” Proceedings: System Sciences. 9pp.

Schramm, K.; Littlewood, T.; Schra, S.; Fitzgerald, W. (2003) “Taguchi tackles diminishing manufacturing sources - a novel approach to using Taguchi design of experiments in recapturing a critical production capability [military parts]” AUTOTESTCON. Proceedings: IEEE Systems Readiness Technology Conference. 588 – 596

Sneed, H.M. (1995) "Planning the reengineering of legacy systems" IEEE Software, 12(1):24 – 34

Sterman, John D. (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World, McGraw-Hill Companies, Inc.

Stogdill, R.C. (1999) "Dealing with obsolete parts" IEEE Design & Test of Computers, 16(2):17 – 25

Towill, D. R. (1991), "Supply chain dynamics." International Journal of Computer Integrated Manufacturing, 4:197 - 208.

Towill, D.R. (1993) "System dynamics- background, methodology and applications. 1. Background and methodology" Computing & Control Engineering Journal, 4(5):201 – 208

Towill, D.R. (1993) "System dynamics-background, methodology and applications.2. Applications" Computing & Control Engineering Journal, 45(6):261 - 268

Towill, Denis R. (1996a) "Industrial dynamics modelling of supply chains." International Journal of Physical Distribution & Logistics Management, 26(2):23 - 42

Towill, Denis R. (1996b) "Industrial Dynamics Modeling of Supply Chains" Logistics Information Management, 9(4):43-56

Trowbridge, P.L.; Hokinson, S. (2002) "EHS supply chain management at Advanced Micro Devices, Inc" IEEE International Symposium on Electronics and the Environment, :209–213

Van Ackere, A.; Warren, K.; Larsen, E. (1997) "Maintaining service quality under pressure from investors: a systems dynamics model as a hands-on learning tool." European Management Journal, 15:128-137.

Wang, Ming; Zhang, Shu. (2005) "Integrating EDI with an E-SCM System Using EAI Technology" Information Systems Management, 22(3):31-36

Wilson, J.R. (2002) "Global war on terrorism intensifies the problem of obsolete parts." Military & Aerospace Electronics, 13(11):18-23