Applying System Dynamics Approach to the Supply Chain Management Problem

by

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Abstract

Supply chain management is one of the fundamental issues in the manufacturing and operation management. The performance of supply chain management directly affects an organization's overall performance. For the past several years, supply chain management has been a growing concern in modern manufacturing and business processes because of the complexity of products and new technologies. Especially, information technology and widespread usage of web-based systems are changing strategies of how companies manage their operations, supply chain structures and strategic alliances.

A supply chain network by nature is a large and complex, engineering and management system. To understand its structure and to design effective policies, the internal dynamic behavior of the supply chain must be studied. System dynamics is an effective tool for understanding the structure and internal dynamic behaviors of a large and complex system. This thesis focuses on a supply chain problem at LSMC. Traditionally, LSMC is an engineering, technological and manufacturing driven company and its products have been dominant in the market for many years. For the past few years, however, the greater competition in the industry and the increasing pressures from the upstream and downstream of LSMC's supply chain have created interesting dynamic behaviors. The purpose of this thesis is to apply system dynamics methodology to LSMC's supply chain problem and potentially apply the framework of this thesis to general supply chain problems in other industries. The thesis includes various simulations and analyses to understand the problem. Especially eigenvalue elasticities approach provides significant insights, which deepen the understanding of the structure of the model and its dynamic behavior, and lead to the conclusion that the oscillatory behavior in the production inventories and in the demand for LSMC's products is an endogenous cause.

Thesis Supervisor: James H. Hines
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Chapter 1 Introduction

1.1 System Dynamics and Supply Chain Management

For several decades, system dynamics has been used as a management tool for understanding real world behavior and implementing strategic policies. System dynamics is an approach for exploring the nonlinear dynamic behavior of a system and studying how the structure and the parameters of the system lead to behavior patterns. Another fundamental purpose of system dynamics is to design effective and robust policies, which enhance performance in managed systems. Undoubtedly, poor policies can give poor performances and potentially unexpected and undesirable behaviors.

One of the classical business problems is supply chain management. The purpose of supply chain management is to provide the right quantity of the right product at the right time to the right customers at an optimal cost. The performance of supply chain management directly affects a company's overall performance. For the past several years, supply chain management has become more important in modern manufacturing and business processes. Recent advances in technology, especially in information technology and widespread usage of web-based systems, are changing strategies of how companies manage their operations, supply chain structures and strategic alliances. Today, many companies exploit new technologies and strategies to improve their supply chain operations. Moreover, collaboration and exchanging information through the near real-time networks have also changed the way the companies carry their inventories and manage their production plans. However, some of the new strategic policies may cause unexpected and undesirable consequences.

To understand those behaviors, it is necessary to understand the structure and dynamics of how an inventory manager manages his inventories and resources. System dynamics is a powerful tool for studying the dynamics of the supply chain and its policy design. Supply chains involve multiple chains of stocks and flows. Three major characteristics of the supply chain are oscillation, amplification and phase lag. These behaviors frustrate people who manage supply chains and attempt to maintain the level of inventories. As these downstream stakeholders, such as customers and retailers, changes their orders, those upstream stakeholders, such as vendors and manufacturing, responds by balancing the rate of using their resources and the rate of production. These balancing policies are always controlled by negative feedback. With the time delays in the supply chains, such as lead-time in manufacturing, transportation delay and information delay, the systems are prone to oscillation.

The purpose of this thesis is to apply system dynamics methodology to LSMC's supply chain problem. Traditionally, LSMC is an engineering, technological and manufacturing driven company and its products have been dominant in the market for many years. For the past few years, however, the higher competitions in the industry and the more pressures from both upstream and downstream of LSMC's supply chain have created interesting dynamic behaviors.

1.2 Thesis Outline

This thesis will focus on how the system dynamics methodology can be applied to the supply chain problem. The thesis is structured as follows:

Chapter 1 states the goal of the thesis and provides thesis outline and a description of the system dynamics methodology. Chapter 2 presents a general supply chain framework and explains LSMC's concerns about its supply chain network and management. Chapter 3 discusses the list of variables and the reference modes that capture LSMC's concerns. Chapter 4 describes the causal loop diagram that explains the reference modes. Chapter 5 discusses the momentum policies and the momentum policy/causal loop mapping, which explains how the momentum policies are related to LSMC's concerns. Chapter 6 presents LSMC's supply chain model through simulations and analyses. Chapter 7 analyzes the model by using different tools such as linearization method, eigenvalue analysis, and eigenvalue elasticities. Chapter 8 summarizes the thesis and offers insights, useful recommendations, reflections and ideas for potential future work.

1.3 System Dynamics Methodology

The project was conducted by using the standard system dynamics method, which captures good practice in general use by system dynamics practitioners (See Hines (2000)). The standard method is the sequence of activities to study a particular problem and these steps are:

1) Problem definition
    a) List of variables - The variables that people think are important to the problem. These variables should be quantifiable or at least people should have ideas how these variables behave (, e.g. increasing or decreasing over time).
    b) Reference modes - A set of graphs for the most important variables, referring to the problem. The reference modes represent historical behavior and projected behavior, which include hopes and fears for the future. These graphs should be presented over time scale, e.g., weeks, months or years.
    c) Problem statement - The real concern of the company.
2) Momentum policies - The policies, or actions, that would be implemented today, with no further time to collect data, to solve the concerned problems.
3) Dynamic hypotheses or causal loop diagram - The hypotheses that describe feedback processes capable of generating the patterns in the reference modes.
4) Modeling of the first loop
5) Analysis of the first loop
6) Modeling the second loop
7) Analysis of the second loop
8) Modeling of the n^{th} loop
9) Analysis of the n^{th} loop
10) Recommended policies

Note that it is not necessary to model all the loops. Insights and conclusions may surprisingly emerge at any step during the process.

Chapter 2 LSMC's Supply Chain

2.1 General Supply Chain

A supply chain is a network of facilities that procure raw materials, transform them into intermediate goods and final products, and deliver the products to customers though a distribution system. A typical supply chain comprises five elements: suppliers, manufacturers, distributors, retailers and customers. The integration of these elements requires coordination of the functions of production planning, purchasing, material management, production, distribution, transportation, customer service and sales forecasting. Supply chains have become a common issue for many companies. In large organizations, the management of this integration becomes very complex. This complex management is even more challenging if the supply chain includes suppliers' supply chain and customers' supply chain in the scope as an inter-enterprise network. Effective supply chain management relates not only to the company's ability to be responsive inside the company, but also to the company's ability to share the information outside among others in the supply chain network.

From a system dynamics viewpoint, a supply chain consists of the structure of feedback loops that control stocks of inventory and capacity as well as flows of production and shipping. A supply chain often involves more than one organization, e.g. suppliers, the company, distribution channels and customers. These normally involve multiple chains of stocks and flows, and often delays from the decision rules controlling the flows. Three major characteristics of the supply chain are oscillation, amplification and phase lag. These behaviors frustrate people who manage supply chains and attempt to maintain the level of inventories because they often ignore such delays. To understand these behaviors, it is necessary to understand the structure and dynamics of how an inventory manager makes decisions about his inventories and resources as he attempts to balance production with orders. These balancing policies always engage negative feedbacks that involve adjusting the state of the system to the desired state by a corrective action to eliminate any discrepancy. Often, there are lags between the control action and its effect and between a change in the stock and the perception of the change by the policy maker. The duration of these lags may vary depending upon the inventory manager's actions.

2.2 LSMC's Supply Chain

Because most LSMC's products are technological gadgets and Personal Computer (PC)'s complimentary products, the sales of LSMC's products, thus, are directly related to the growth of PC market. The growth of the PC market has been very strong in the past few years (Table 2.1) and it has dramatically driven sales of LSMC's products in the 1990's as well.

Table 2.1 Worldwide PC Shipment Growth *

Year	Shipments (millions)	%Growth
1994	47.3	--
1995	59.5	25.8%
1996	70.2	18.1%
1997	81.4	15.9%
1998	91.9	12.8%
1999	113.5	23.6%
2000	134.8	18.8%
2001(est.)	157.2	16.6%

*Source: International Data Corp. (IDC)

Even though LSMC has maintained its market share, LSMC experienced competitive pressures and demand fluctuation in the market, which in turn impacted its supply chain strategies. Approximately, LSMC has over 500 suppliers. To minimize the bargaining power of any one supplier, for each particular component, LSMC employs several supplier companies. LSMC also insists that its suppliers provide excellent quality, are on time and offer competitive low prices. However, for the past few years, the PC industry and the market of PC complimentary products have become more competitive. LSMC had been concerned with improving its supply chain strategies.

As market leader, LSMC supplies its products to Original Equipment Manufacturers (OEMs) like Compaq, Dell, Gateway and Hewlett-Packard. Especially, Compaq and Dell are LSMC's largest customers. Since 1998, led by Dell, many OEMs have changed their strategies by aggressively eliminating slack from the supply chain through Build-To-Order (BTO) manufacturing and Just In Time (JIT) processes that eliminate inventories of raw materials, components and finished products, and operate on only seven days or less of supply inventory. As a result, LSMC and other stakeholders in the PC supply chain now face even greater pressure to coordinate, integrate and share information of their supply levels, manufacturing capacity and inventory. Because of fast dynamic changes in the PC market, the short life cycle of PC and other complimentary products has also amplified coordination problems, which in turn have often caused the excess inventory of PC components. Moreover, because the PC demand fluctuates and the PC market is unpredictable, LSMC, occasionally, is not able to keep up with the demand. LSMC needs to track such market details as how many customers are buying LSMC's products so it can predict the short term and long term demand forecasts more effectively.

Another main factor in LSMC's supply chain problem is the stiff competition from other companies, which produce similar types of products. These companies have introduced high performance and greater variety of products that may potentially erode LSMC's existing market share. The competition has led LSMC to introduce more and better products to the market to protect its existing and potential market share. As a result, LSMC's actions exacerbate its supply chain problem.

LSMC's production capacity is another factor that adds to LSMC's supply chain complexity because of its long delay and huge investment. At present, it takes LSMC about two years to build a new plant. Furthermore, LSMC's new products have a more complex manufacturing process than do the previous generations. This obviously means much greater costs for LSMC, which will counterproductively erode its profit margins.

Many of LSMC's products are at the upstream of the supply chain for PCs and fluctuate more than PC production. Given the complex and dynamic nature of the industry, the supply chain at LSMC is a large and complex, dynamic issue. It is difficult for LSMC to see how its policy decisions and actions might impact its performance or cause unexpected and undesirable consequences. In the next chapters, system dynamics is applied as a tool to help understand these problems and identify the cause of the problem.

Chapter 3 Problem Definition

In Chapter 2, the discussion of LSMC's supply chain leads to the question of what are the major concerns in LSMC's supply chain and which parameters in LSMC's supply chain may contribute to those concerns.

System dynamics' standard method (See Hines (2000)) is used as a framework to study LSMC's supply chain problem. The first step of system dynamics is 'Problem Definition' which consists of 1) List of Variables, 2) Reference Modes and 3) Problem Statement. The process of conducting 'Problem Definition' is described in this chapter.

During the study of LSMC's supply chain, the interviewed participants came from various departments in LSMC. The participants included a senior manger from information technology department who was specialized in LSMC's supply chain network and strategic planning, a manger from manufacturing department, a manager from a strategic planning department, two managers from supply chain department, and also engineers and scheduling planners from those departments. Hence the inputs and opinions may vary from person to person or from department to department.

3.1 List of Variables

The project started with interviewing the senior managers from various departments who have been involved in the supply chain at LSMC for many years. The participants were asked to identify significant variables that they thought would impact LSMC's supply chain operations. These variables are listed in Appendix A.

After generating the list of variables, each participant then was asked to vote for six variables that he or she thought were the most important to their problems. The six variables are with the most votes were:

1. Capacity
2. Demand
3. Inventory
4. Cycle Time
5. Cost
6. Forecast Accuracy.

Starting with these six variables helped to clarify several issues. For example, some of the selected variables, such as cost and inventory, have different meanings to different participants from different departments. Several participants also mentioned that Forecast Accuracy is an ambiguous variable because it is difficult to be quantified. Some variables such as Demand and Inventory have similar patterns, which indicated they might be directly involved in the same feedback loops. The variables represented in reference modes, should describe different parts of the system. Note that these variables may not be the most important variables in LSMC's supply chain problem but these variables are a starting point for the next step, creating reference modes. The team decided to choose the following variables:

1. Product Life Cycle
2. Capacity Relative to Desired Capacity
3. Change in Customer Orders
4. Material Inventory Write-offs
5. Average OEM Margin.

3.2 Reference Modes

A reference mode is a graph representing historical behavior and projected behavior, which include hopes and fears for the future, of the variables that people are interested. Note that it is not necessary to draw reference modes in precise scale. Trends and behaviors, such as increasing, decreasing, or oscillating over time are sufficient. The next step of 'Problem Definition' was to draw the reference modes of the variables that the team were interested in. In the subsequent meeting, the participants were asked to draw the reference modes of those variables.

3.2.1 Product Life Cycle and Demand of LSMC's Products

The technology of LSMC's products has undergone several generations of changes. For every product, there is a set of principles that govern the life expectancy of the product. This product life cycle (see Figure 3.1) is marked by various events and periods, and how each product is viewed by the consuming public over time.

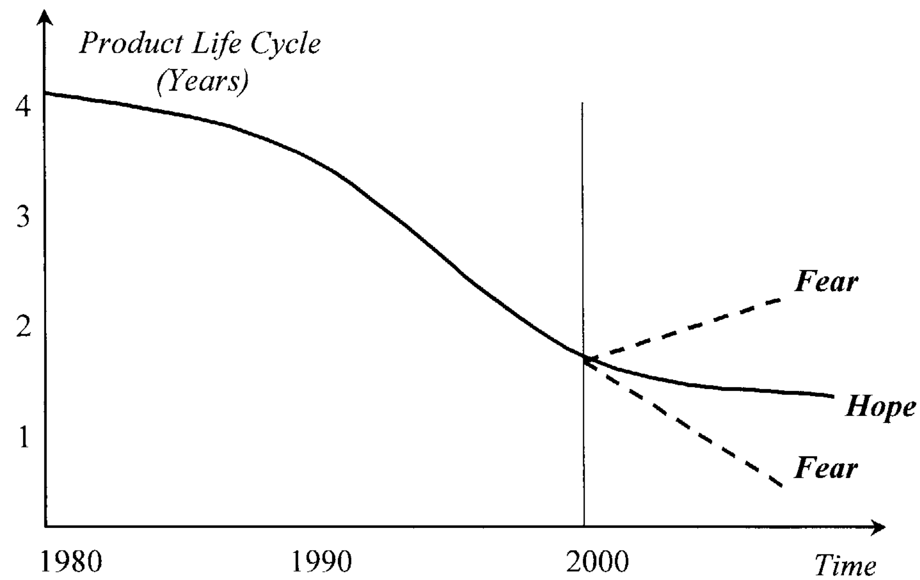

Figure 3.1 Product Life Cycle

The rapid improvement of technology and the intense competition in computer industry reduce the life cycles of LSMC's products (see Figure 3.2). Product A had a low demand and long product life cycle. The demands for the later generation products (B, C and D) were higher but the product life cycles were shorter. The hope is that the product life cycle would not decrease at an even faster rate by new technology disruption.

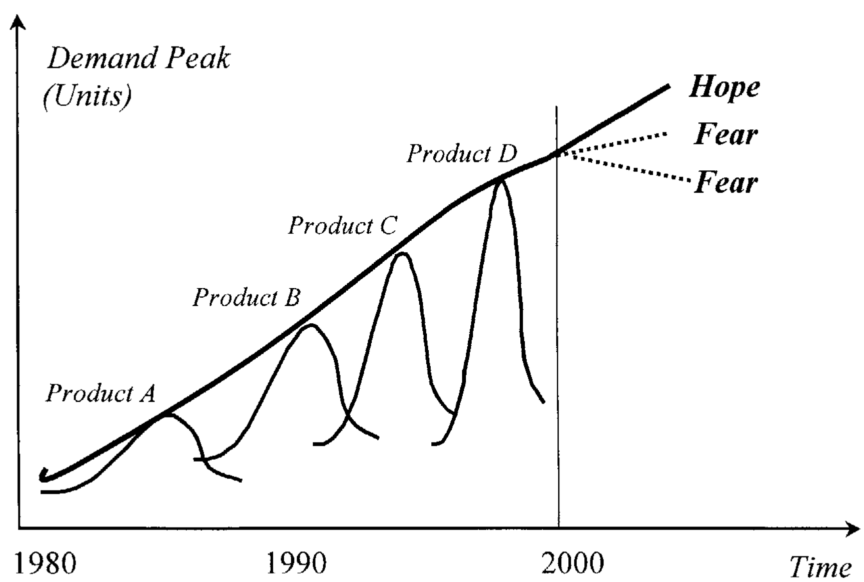

Figure 3.2 Demand of LSMC's Products

Note that the market segment was not strongly divided for the early generation products (A, B and C). For product D, LSMC introduced different versions for different market segments. For example the cheapest and limited features products are for low-end users, the medium range products are for regular users, and the most expensive and most powerful products are for professional and high-end users. The segmentation was one of LSMC's strategies to prolong its product life cycles.

3.2.2 Actual Capacity Relative to Desired Capacity

In 2000, LSMC increased its capital-spending budget from 1999. Ramping up the production capacity helps LSMC to take advantage of economy of scale. However, because of the demand fluctuation and rapid changes in the PC market, LSMC, occasionally, is not able to respond to demand.

The participants believe that LSMC's capacity relative to desired capacity oscillates and the amplitude is growing. The participants hope that the cycle and the amplitude will decrease and become more stable in the future (see Figure 3.3).

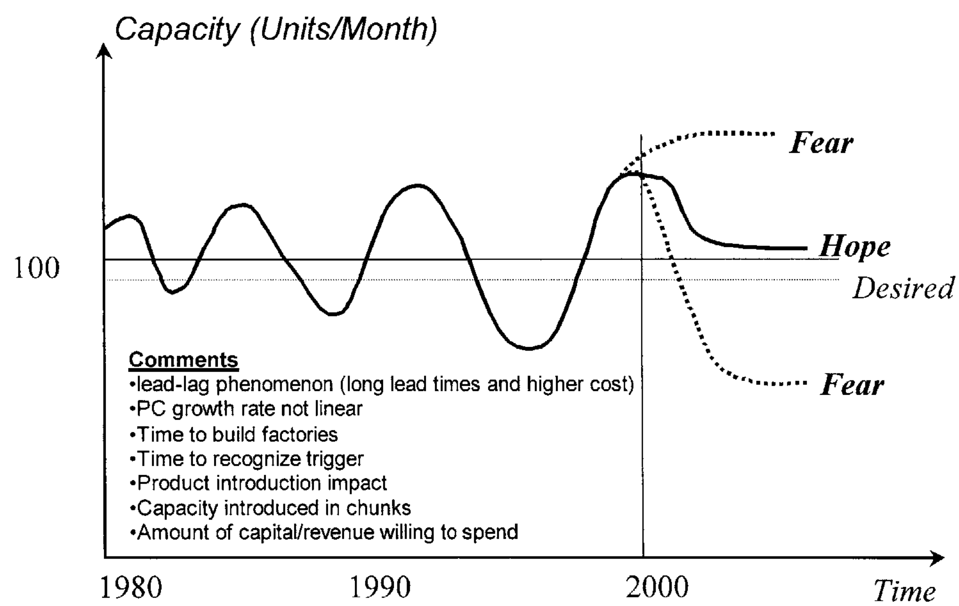

Figure 3.3 Actual Capacity Relative to Desired Capacity

3.2.3 Change in Customer Orders

Not only do OEMs want to carry smaller inventories but they also want to have flexibility to cancel their orders from LSMC. Before the Build-To-Order (BTO) approach was in place in 1999, OEMs operated their inventory by the Build-To-Stock (BTS) approach. OEMs and LSMC agreed to a 60-day cancellation and allocation policy for BTS. However, after BTO, OEMs wanted to further reduce the time of the cancellation. At the time of this study, OEMs and LSMC agree on a one-week cancellation policy. The policy creates a very unstable signal for LSMC's customer orders. The hope is that the signal will be more stable, and the amplitude and the frequency will decrease in the future (see Figure 3.4).

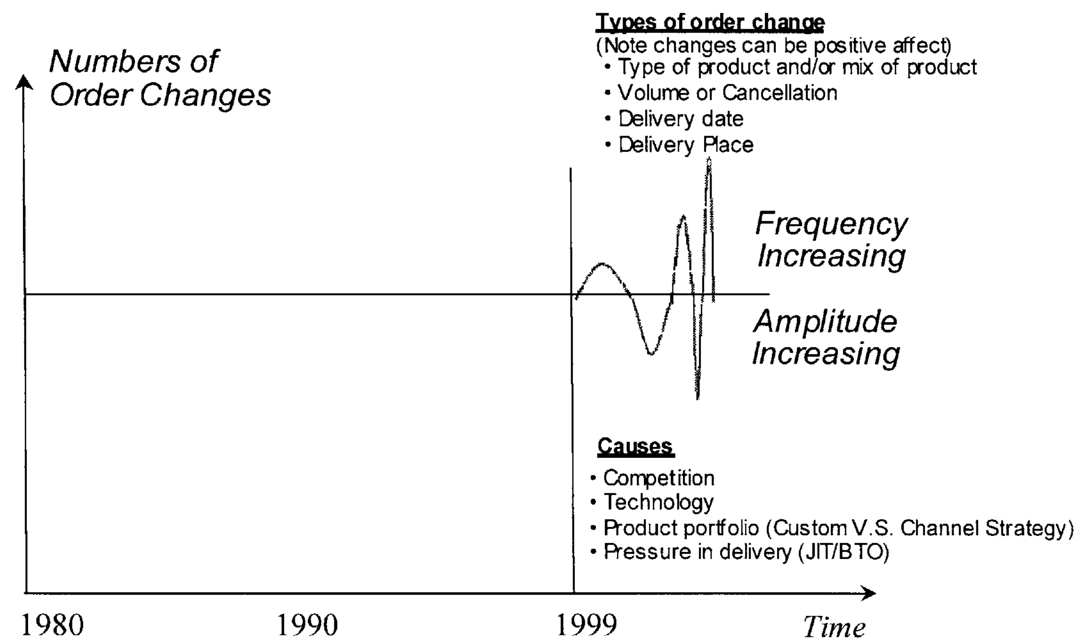

Figure 3.4 Changes in Customer Orders

3.2.4 Raw Material Inventory Write-off

Occasionally some raw materials may be obsolete and LSMC needs to write them off. However, the life cycle of LSMC's products is decreasing and there are more frequent customer order changes. LSMC's concern is that the trend of the write-off is continuing to increase and so is the managerial stress for managing the inventory write-off. Figure 3.5 shows such a concern.

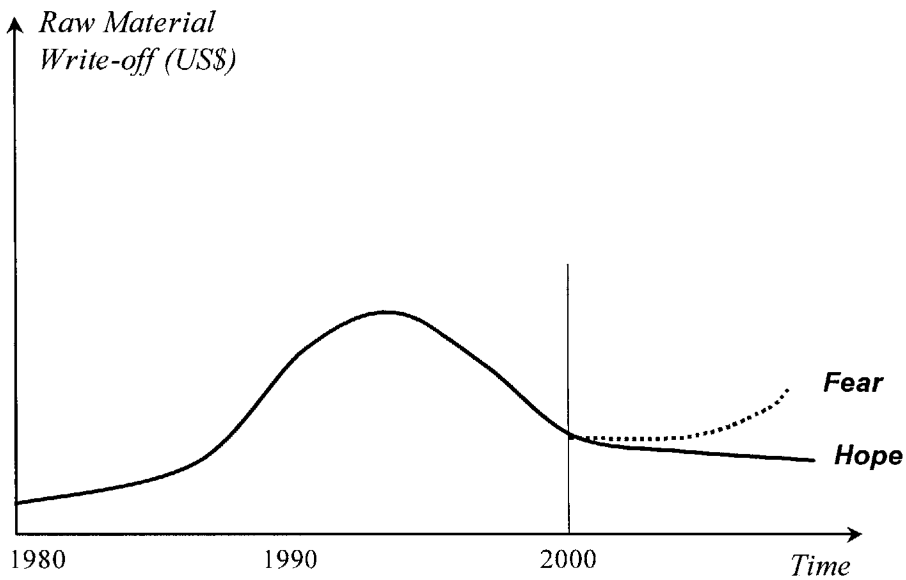

Figure 3.5 Raw Material Inventory Write-off

3.2.5 Average OEM Margin

Because of the increased popularity of the Internet, more people use computers to surf the Internet and send email. PC consumers do not need powerful PCs to perform these simple tasks. To respond to the trend, in 1997, Compaq began offering low-priced PCs for these PC consumer group. Compaq's strategy led to the increased competitions among OEM's. LSMC had to respond by introducing the low-end products to the market. The low-end market has a low margin but has high volume in sales compared to the high-end market, which has high margin. The overall average margin has been declining since the mid 1990's.

The participants are concerned that the average margin might decline further and that would erode the company's overall profit. Figure 3.6 shows the reference mode of Average OEM Margin.

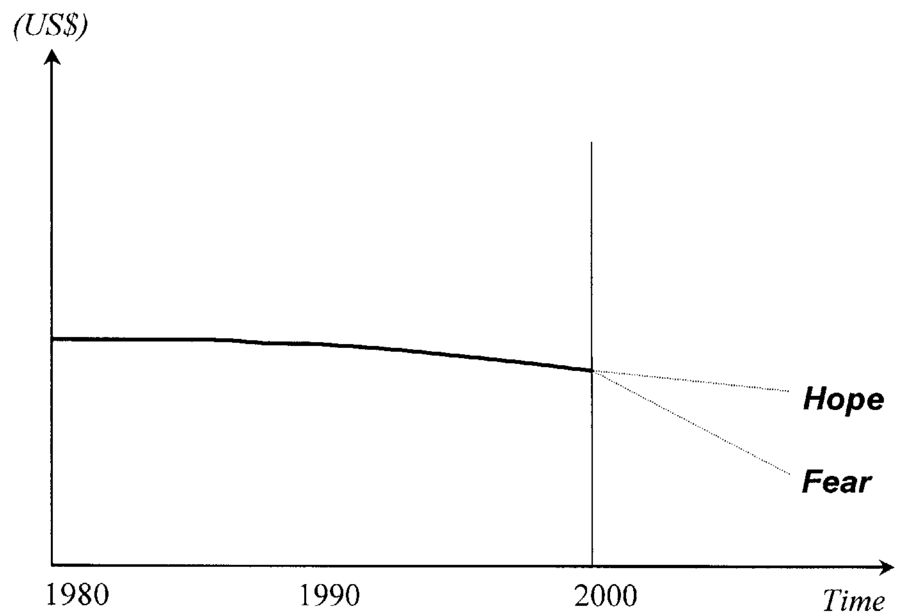

Figure 3.6 Average OEM Margin

Additionally, during the process of creating reference modes for the selected variables, Product Life Cycle, Capacity Relative to Desired Capacity, Change in Customer Orders, Material Inventory Write-offs and Average OEM Margin, several participants in manufacturing and planning also expressed concerned for Pre-assembly component inventory and throughput time of product cycle time, Working In Process

(WIP) inventory, OEM's Inventory and LSMC's Product Inventory. These concerned were captured in the reference modes from Section 3.2.6 to 3.2.9. These reference modes will be useful to explain details in LSMC's manufacturing process for model development in Chapter 6 and model analysis in Chapter 7

3.2.6 Pre-assembly Component Inventory

Pre-assembly components are various components that are created in LSMC and bought from suppliers. The overall pre-assembly component inventory in LSMC's manufacturing process is constantly decreasing, which is a desirable trend. However, LSMC runs a push-pull manufacturing process. At the beginning of the process, a pre-assembly facility pushes components to an assembly and test unit and the finished goods inventory unit pulls from the assembly and test unit. There is a fear that the pre-assembly component inventory may increase because of increasing complexity of production (see Figure 3.7).

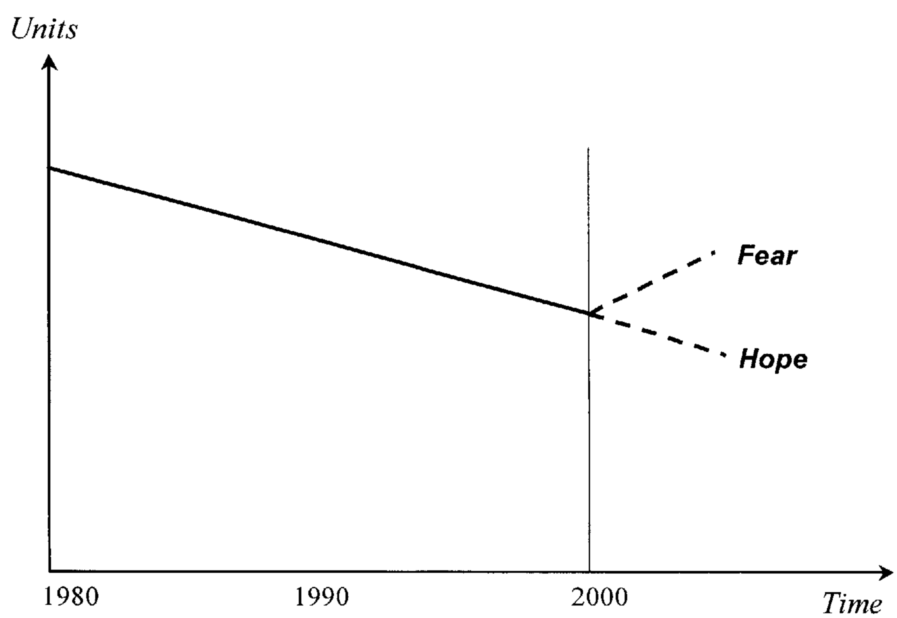

Figure 3.7 Pre-Assembly Component Inventory

3.2.7 Throughput Time of Product Cycle Time and Working In Process (WIP) Inventory

Because of the demand cycle and stiff competition in the PC market, the OEMs want to carry fewer inventories in their process. Also with the increasingly complex process in LSMC's manufacturing, LSMC's throughput time of product cycle time and WIP inventory are increasing, as are LSMC's supplier (see Figure 3.8 and Figure 3.9).

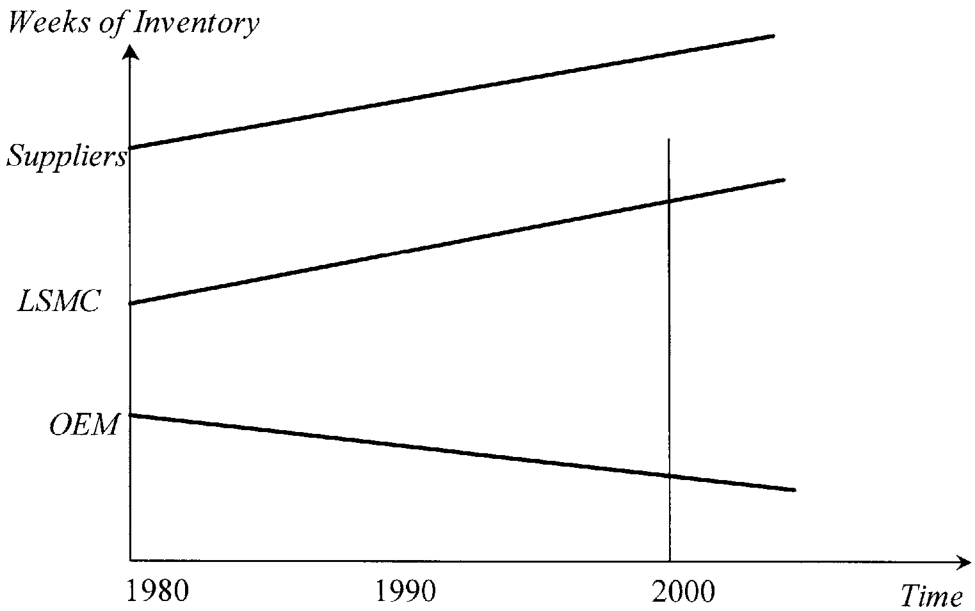

Figure 3.8 Throughput Time of Product Cycle Time

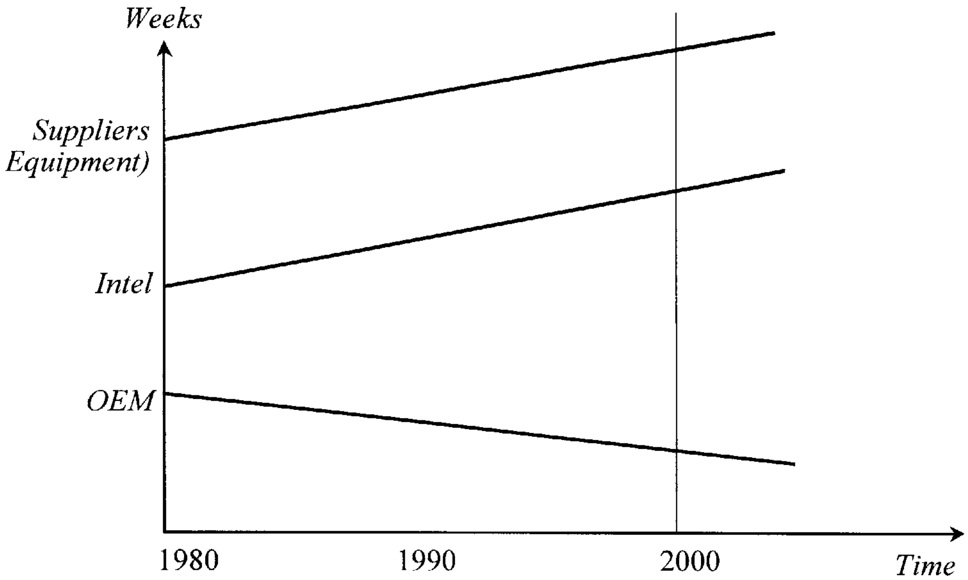

Figure 3.9 WIP Inventory

3.2.8 OEM's Inventory

Since 1997, led by Dell, most of the OEMs have moved to Build-To-Order (BTO) manufacturing and the Just In Time (JIT) process, which aggressively eliminate their inventory of raw materials, components and finished products. Figure 3.10 shows the amount of inventory that OEMs want to carry. The hope is that the trend will not decrease further.

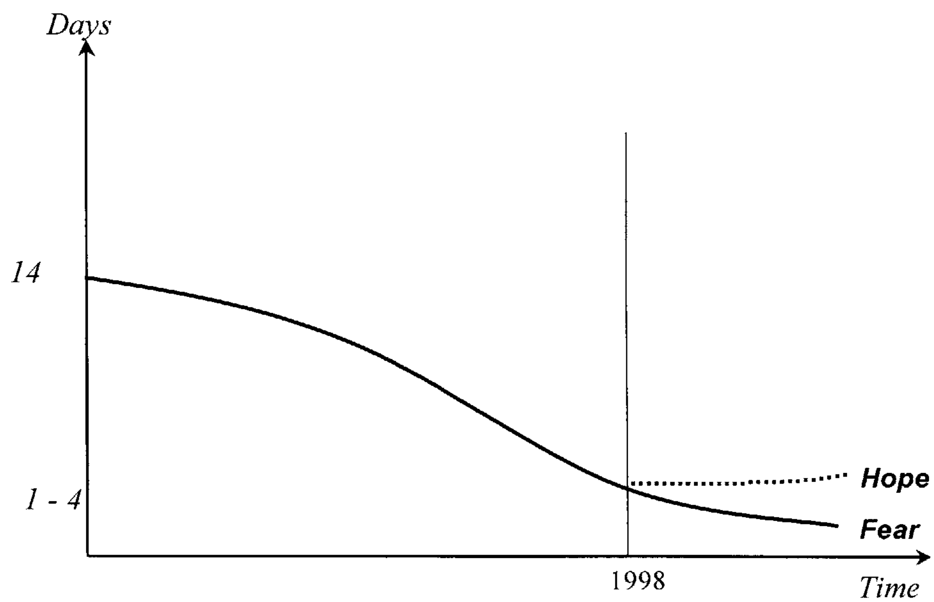

Figure 3.10 OEMs' Inventory

3.2.9 Product Inventory

When the finished goods (FG) inventory is higher than the market demand, LSMC has to carry its FG inventory. Carrying oversupply contributes to storage costs and might create a risk of losing revenue due to product obsolescence. However, when LSMC carries products less than the market demand, stock-outs occur and LSMC may lose opportunities to sell its products and decrease its revenue. LSMC's concerns are the loss revenue of the mismatch between the FG inventory and the market demand and it wants how to minimize the effect of the risk of product obsolescence and loss of the potential revenue (see Figure 3.11). This reference mode also captured a growth pattern in Product Inventory as well.

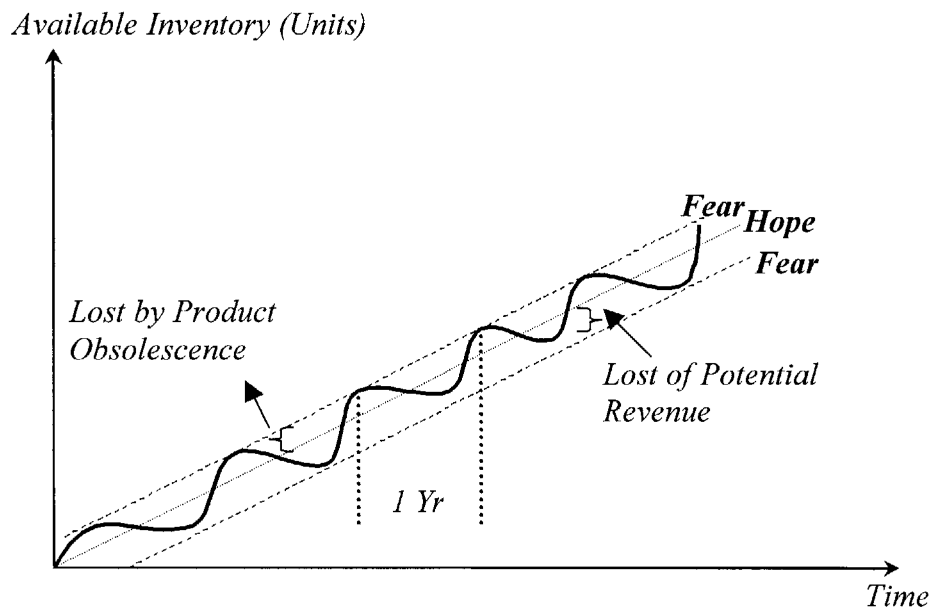

Figure 3.11 Product Inventory

3.3 Problem Statement

After drawing the reference modes, the behaviors that most participants concerned are the fluctuations of the reference modes, Product Inventory (see Figure 3.11) and Actual Capacity Relative to Desired Capacity, (see Figure 3.3). Moreover, general supply chain systems are prone to oscillation as explained in Section 1.1. It would be interesting to study what cause such oscillatory behaviors in LSMC's supply chain system. So the problem statements are defined as follows:

1. The fluctuation in the finished goods (FG) inventory oscillates and the amplitude is large compared to demand and capacity.

2. LSMC's capacity relative to desired capacity oscillates and the amplitude is growing.

Chapter 4 Momentum Policies

The next step for the system dynamics approach is generating momentum policies. Momentum policies are the policies or actions that LSMC would implement today, with no further time to collect data to solve the problem. Momentum policies clarify what solutions are implemented, being implemented or considered to implement. Momentum policies can also used as a tool to learn how the participants are thinking of solving problems.

Before the process of creating momentum policies, the participants started with LSMC's current policies which were captured in Section 4.1. The momentum policies which LSMC's participant considered to implement to solve the problems identified in Section 3.3, are presented in Section 4.2.

4.1 Current Policies

At the time of this study, LSMC has policies in place. These are the current policies that the company has implemented:

1) Corporate Commitment Process – CCP

This policy is a product allocation scheme. Decisions are made in weekly meetings to provide a leveled playing field to customers without any preferences. LSMC provides a list of available inventory and OEMs book orders according to availability.

2) Responsiveness to competition

If any competitor threatens to introduce a new product with high performance, LSMC will immediately respond. LSMC makes a commitment to offer the best product performance to the computer market. It can effectively take action in product performance, design changes, reprioritization, packaging and process design.

3) Planning policies

LSMC runs a push-pull manufacturing process. At the beginning of the process, a pre-assembly facility pushes to an assembly and test unit and a finished goods inventory pull from the assembly and test unit. There are two inventory policies:

i) Build to forecast: supplier-centric, front end

ii) Build to order: customer plan replenishment

4) LSMC principle

i) Run the production by having the pre-assembly facility as the constraint. The assembly and test unit and materials are not constraints.

ii) Drive its performance.

iii) Have its capacity to meet demand.

5) Material policies

i) At start-up:

- Inventory can be high.
- Cost is not an issue.
- Ramping up should not be done and having enough inventories.
- Risk can be high when building new products, e.g. using riskier suppliers.

ii) At mid-cycle:

- Attempt to drive costs down.
- Reduce risks by including multiple suppliers.

iii) At end of ramp:

- No write-offs.
- No excess inventories.
- Risk should be minimized.
- Cost may increase.

6) Silo Performance Measurement

Metrics are in tension with each other. Some of those matrices occur by chance and others occur by design.

7) Distributing Production Schedule

Decrease production risk by distributing a production schedule. Any process or product gets made in more than one factory; each factory makes more than one product.

4.2 Momentum Policies

The participants were asked to state what they would do at the time to solve the problems that they were encountering. The policies have been categorized into three domains, C – Capacity, D – Demand and P – Production. The relation and effect of each policy is classified as belonging to one or more of these three domains. These are the momentum policies that the participants generated.

Table 4.1 Momentum Policies

C – Capacity D – Demand P – Production

C	D	P	#	Momentum Policies
	D		1	Supply Line Management (SLM) - to reduce changes in customer orders. Effort to help customers manage their inventories and potentially reduce the range of change in customer orders.
	D		2	Performance Competitive Responsiveness - to increase market share by offering best performance to beat the competition.
	D		3	Price Competitive Responsiveness - to increase market share by lowering prices and quickly transitioning to a new architecture and a new product family to beat the competition.
	D		4	Understand and reduce the impact of demand variability
	D		5	Raise prices to control for increases in demand. This focused responsiveness to demand is advocated only when there are big shifts in demand and the competition does not have the capacity to supply. Then, in the short-run, LSMC does not have to invest in capacity, and it can sell products at a premium.
C	D		6	Always invest in new capacity to control for increases in demand. If competitors have sufficient capacity then LSMC has to invest to maintain market leadership. If they do not, raising prices may not work in the long-term for two reasons. LSMC may under-invest in capacity and reduce its ability to supply. It may induce competitors to invest more heavily in capacity expansion.
		P	7	Burst Capacity Assembly Test - to increase short-term supply. This can be used to increase short-term demand shortages and also to deal with hockey-stick problem imposed by customers at the end of each quarter.
		P	8	Theory of Constraint Policies – This can help LSMC to reduce the impact of demand variability on its pre-assembly units operation. Choose constraint based on capital costs/value, newness of technology modules, granularity of equipment, position of process flow, and joint protective capacity
		P	9	Consider short-run production plan on all pre-assembly units instead of disaggregate plan on each pre-assembly.
		P	10	If it takes 3 weeks for pre-assembly units to respond to changes in orders, then cut response time.

		P	11	If it takes 3 weeks for pre-assembly units to learn whether the response to changes in orders is good or bad, then reduce the figuring time.
		P	12	Scrap material right after leaving the pre-assembly instead of packaging them first.
		P	13	Improve interchangeability and flexibility on production capacity and processes (process technologies have been diverging over time.).
		P	14	Improve the output capability of a constrained tool, such as high cost equipment, under demand variability.
C			15	Use subcontractor capacity appropriately and prevent them from becoming the competitor.
C			16	Improve forecasting to facilitate a better decision making for capacity
				If demand < supply, then:
	D		17	Sales/Marketing Effort - to generate more demand.
	D		18	Killer Apps Development - to create a new market with killer apps.
		P	19	Cost Control Effort – to tighten the belt on factories and reduce costs and to deal with the financial impacts of low demand.
		P	20	Product Interchangeability Effort
		P	21	Capacity Ramps Policy – to adjust the speed of equipment introduction to ramp production according to actual demand.
C		P	22	Make It In-house - to reduce fraction of work at subcontractors, bring more of the work in-house
C			23	Delay Factory Start-ups - to avoid tying up/spending capital for production that will not be used.
C			24	Stop Delay Factory Start-ups- to avoid the strategic over-reaction problem of delaying the introduction of new pre-assembly units.
				If demand > supply (example: Q4 1999)
		P	25	Push For More Output – to increase efficiencies in capacity and decrease throughput times to increase production in the short-term.

		P	26	Accelerate the Rate of Improvement in Design and Manufacturing
		P	27	Prioritize Production – to focus on high-end market, the demand that has high profit margins, and give up the low-end market segments.
C		P	28	Buy-it Outside – to use subcontractors to produce more in the short-term.

The momentum policies will be additional useful information to create dynamic hypotheses or causal loops in Chapter 5 . Moreover, insights of the mapping of the momentum policies on the causal loop diagram will be present in Chapter 5 as well.

Chapter 5 Causal Loop Diagram Development

This chapter explains how the causal loop diagram is constructed and the ideas behind each loop. From the list of variables, the reference modes and the interviews with the participants, the team developed dynamic hypotheses or causal loop diagrams that explain the dynamic behaviors of the problems. Figure 5.1 shows the complete causal loop diagram. How this diagram is constructed will be discussed in the next sections.

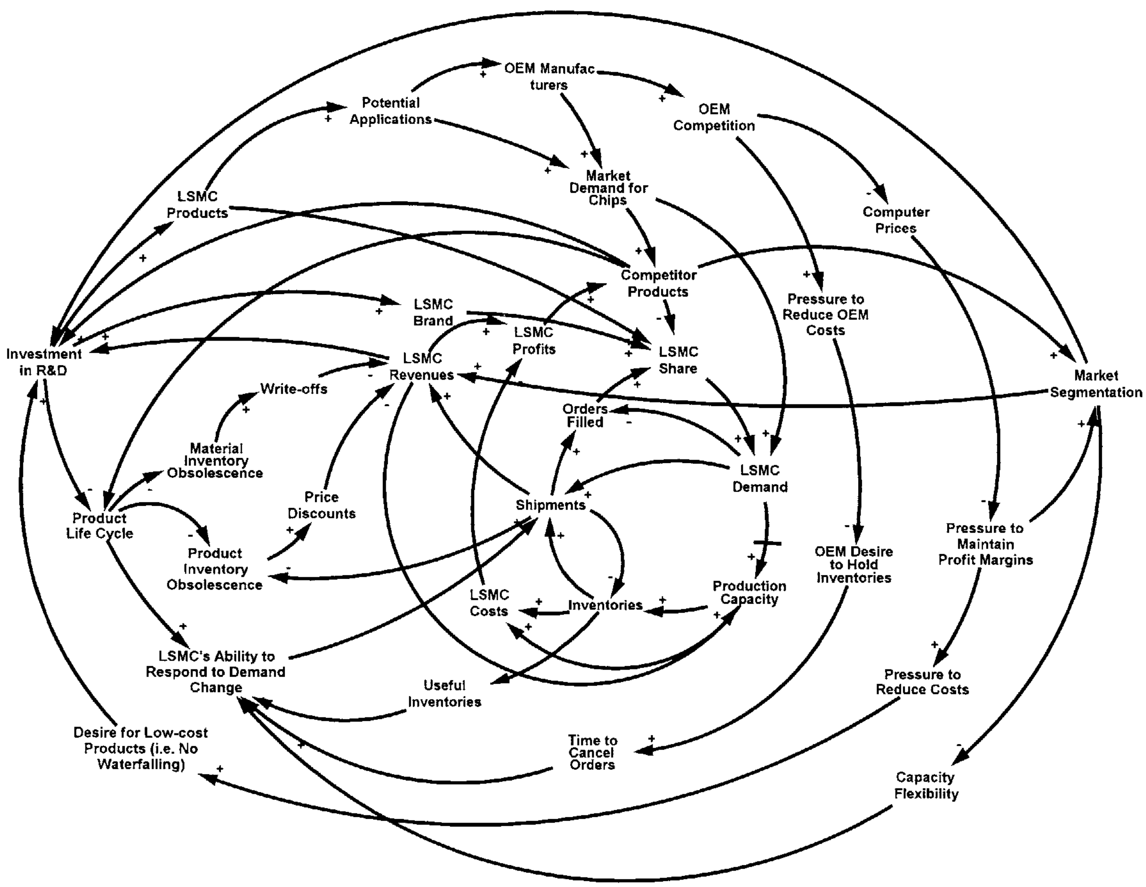

Figure 5.1 Complete Loop Diagram

5.1 If you make it, they will come

With the growth of PC market (See Section 2.2), LSMC has introduced several product generations and LSMC's subsequent generations always generated more growth than its previous generations (See reference mode in Section 3.2.2). The first hypothesis explains the relationships among LSMC's production capacity, market share and demand. As LSMC increases its production capacity, it will be able to produce and ship its products and fulfill its customers' orders. As a result, LSMC gains more market share and then generates more demand in the market. Note that there is a delay between the demand and the production capacity. At present, it takes LSMC about two years to build a production facility. The major issues facing LSMC are the ability to produce the right products in appropriate quantities and the ability to have the right capacity at the right moment at an optimal cost. Historically, the demand for computer peripheral and other complimentary products has been relatively stable, reflecting the growth of the PC market and the growth of LSMC's as well. The growth of LSMC's product was captured in the reference mode, Demand of LSMC's Products in Figure 3.2. The loop in Figure 5.2 captures this hypothesis and this loop is a reinforcing loop. The loop also captures the growth pattern (not the oscillatory behavior) of Product Inventory in Figure 3.11.

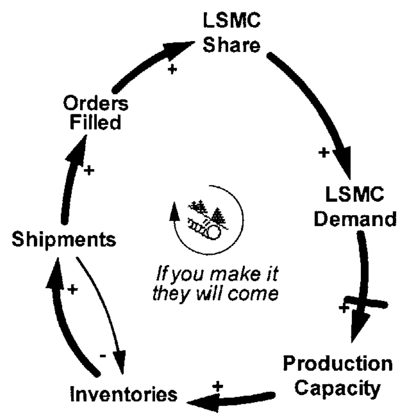

Figure 5.2 If you make it, they will come

5.2 If you ship it, they will come

The reinforcing loop in Figure 5.3 explains how LSMC's ability to deliver affects market share and demand. The more products LSMC can ship to the market, the greater market share it gains. With the network effect, the increase of LSMC's market share creates more installed base and customer demand. This hypothesis also corresponds to the growth of the LSMC's demand in the reference mode in Section 3.2.2.

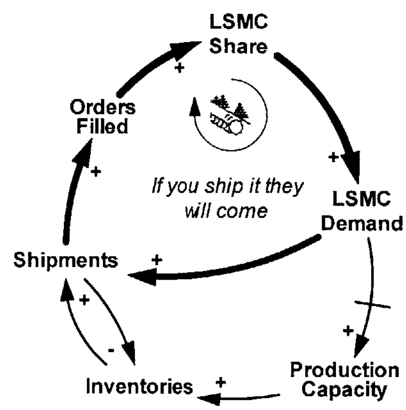

Figure 5.3 If you ship it, they will come

5.3 But if you don't make enough, they'll go way

For the last several years, LSMC's competitors have aggressively created products comparable to LSMC's products. As a result, consumers have more alternatives to choose from. The consumers may buy products from LSMC's competitors, if LSMC cannot fill the consumers' orders; this may deplete LSMC's market share. Figure 5.4 presents the balancing loop that captures this hypothesis.

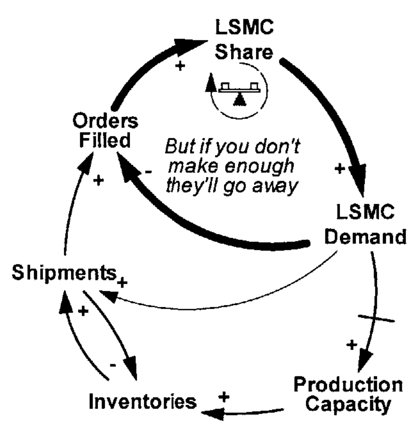

Figure 5.4 But if you don't make enough, they'll go away

5.4 If they come, you can also expand

Figure 5.5 depicts the reinforcing loop that explains how LSMC's ability to ship its products to its customers generates more revenue. LSMC, in turn, will invest more in the production capacity and its related technologies. Furthermore, ramping up the production capacity helps LSMC to take advantage of economy of scale. Because the more capacity LSMC has, the more products LSMC can produce, the hypothesis captures the growth pattern (not the oscillatory behavior) of Product Inventory in Figure 3.11.

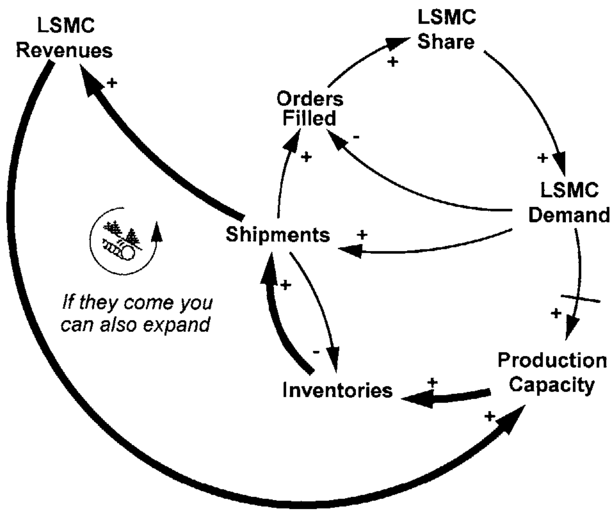

Figure 5.5 If they come, you can also expand

5.5 High profit induce competitor entry

LSMC's high profits encourage competitors to break into the market. Competitors introduce new products, which compete directly with LSMC's existing products. This competition would deplete LSMC's market share and revenue. The balancing loop in Figure 5.6 captures the hypothesis.

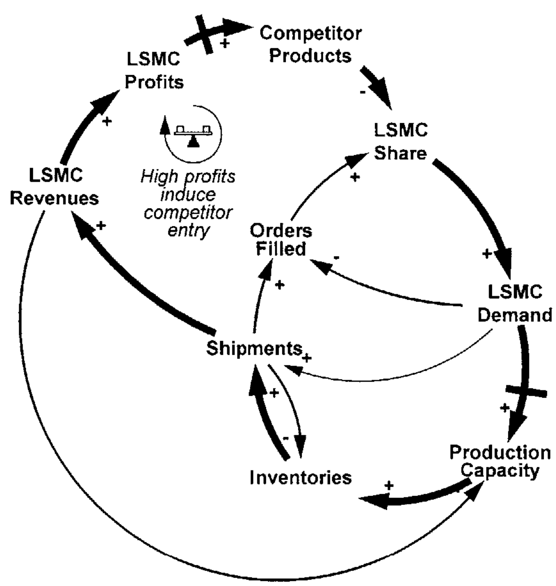

Figure 5.6 High Profit induces competitor entry

5.6 Low profit reduces competitor entry

More competitors in the market will create price pressure on LSMC. After prices drop, the margin shrinks and the market becomes less attractive to other companies, which are considering entering the market. Another barrier to entering the market is the upfront high investment and expense for a production facility. This high price tag discourages new start-to-finish manufacturers. LSMC controls its value chain by designing, developing, manufacturing and marketing its own products. This hypothesis is captured in the reinforcing loop in Figure 5.7.

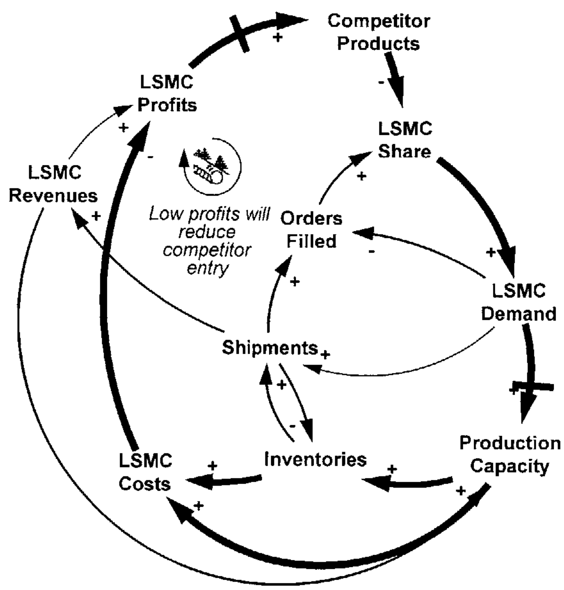

Figure 5.7 Low profit reduces competitor entry

5.7 Producing the right products keeps LSMC growing

Since the life cycle of LSMC's products is short, less than 2 years, and the PC market changes very frequently, the ability to produce the right products in the appropriate quantities and ability to have the right capacity at the right moment at minimal cost keeps LSMC's market share growing. Figure 5.8 presents the reinforcing loop that summarizes this hypothesis. The growth patterns of Demand of LSMC's Products in Figure 3.2. and Product Inventory in Figure 3.11 suggest that LSMC has responded to market well.

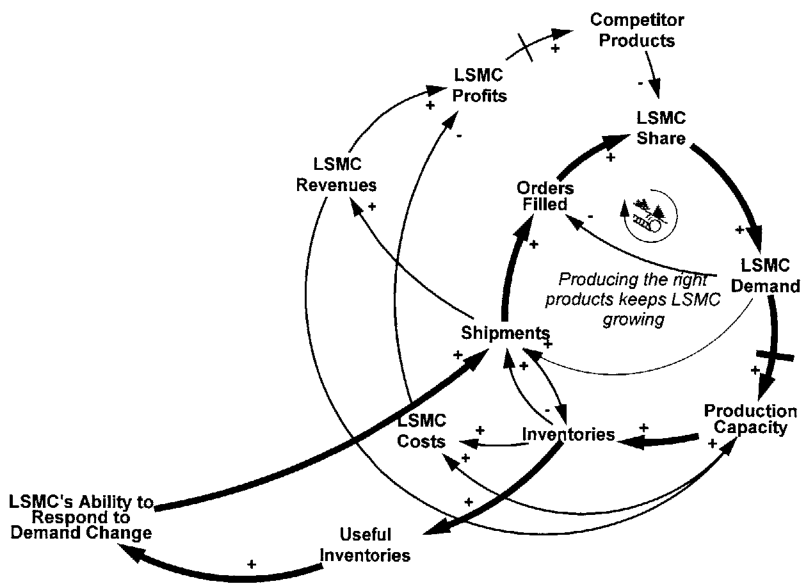

Figure 5.8 Producing the right products keeps LSMC growing

5.8 Engine of growth

Figure 5.9 illustrates three reinforcing loops that create growth for LSMC.

1) As its revenue grows, LSMC will invest more in R&D to create new products. As a result, LSMC would be ahead of other competitors and improve market share. The network effect is also a factor. The size of the installed base of users is built up over time because LSMC has continually introduced new and improved products into the market. By investing in more research and development, LSMC is also able to lower its prices and increase its product performance.

2) The growth of LSMC's demand was originally caused by the success of LSMC products and the LSMC Brand. The LSMC marketing program in the early 1990's has

helped create brand equity. LSMC uses this strategy as a premier marketing vehicle. LSMC's branding has been so successful that end-users turn to LSMC's brand name rather than the computer makers' names. This strategy keeps LSMC in consumers' minds as the premier computer product makers. In many cases, LSMC can still price its products higher than its competitors' products based on its brand name.

3) The mainstream markets still need high speed and powerful products, especially for more complex and faster multimedia. Sophisticated computer users are willing to pay a premium price for the faster and more powerful products, which in turn helps LSMC sell more products.

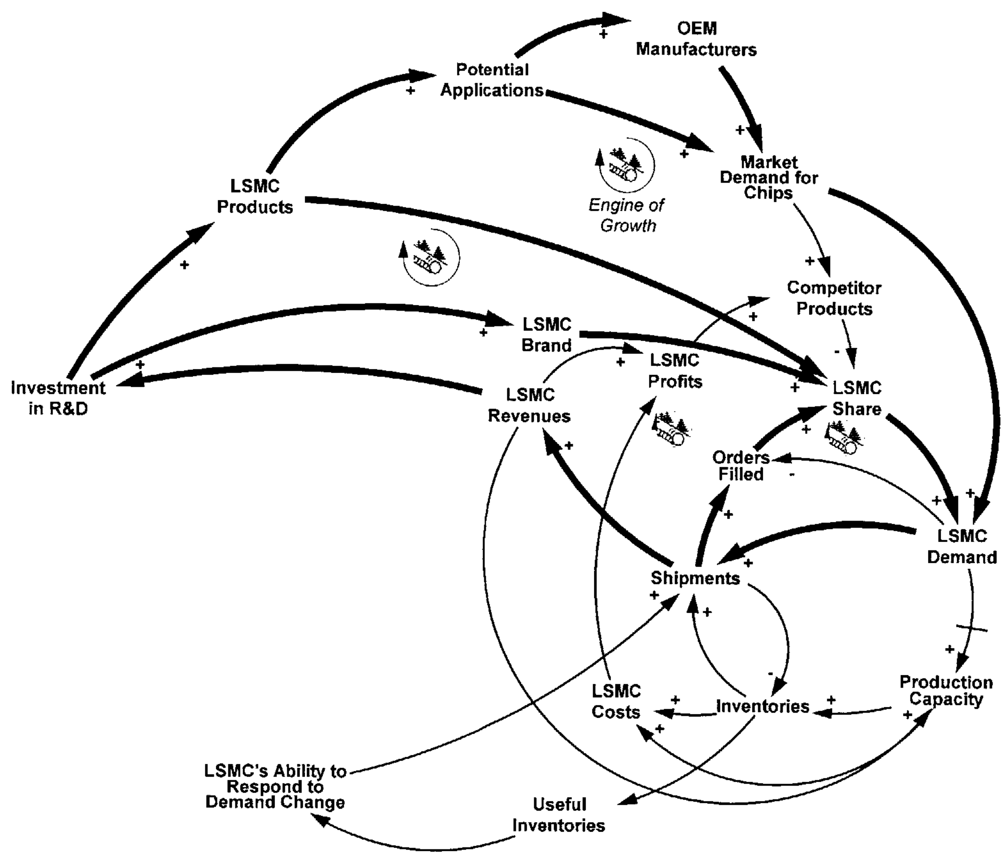

Figure 5.9 Engine of growth

5.9 Inventory obsolescence

The increase of R&D investment decrease the life cycle of LSMC's products which is captured in the reference mode, Product Life Cycle in Figure 3.1. Each new generation of LSMC's products has higher speed and better performance. LSMC forces end users to migrate to its newer technologies. However, this practice puts pressure on the old products. LSMC needs to reduce its prices to accelerate the sale of the old products. As a result, the raw materials ordered for producing the old products may be obsolete and need to be written off. Raw Material Inventory Write-off is one of the reference modes (see Section 3.2.4). Both price discounts and material write-off from inventory obsolescence reduce LSMC's potential revenue. This hypothesis is presented in the balancing loop in Figure 5.10.

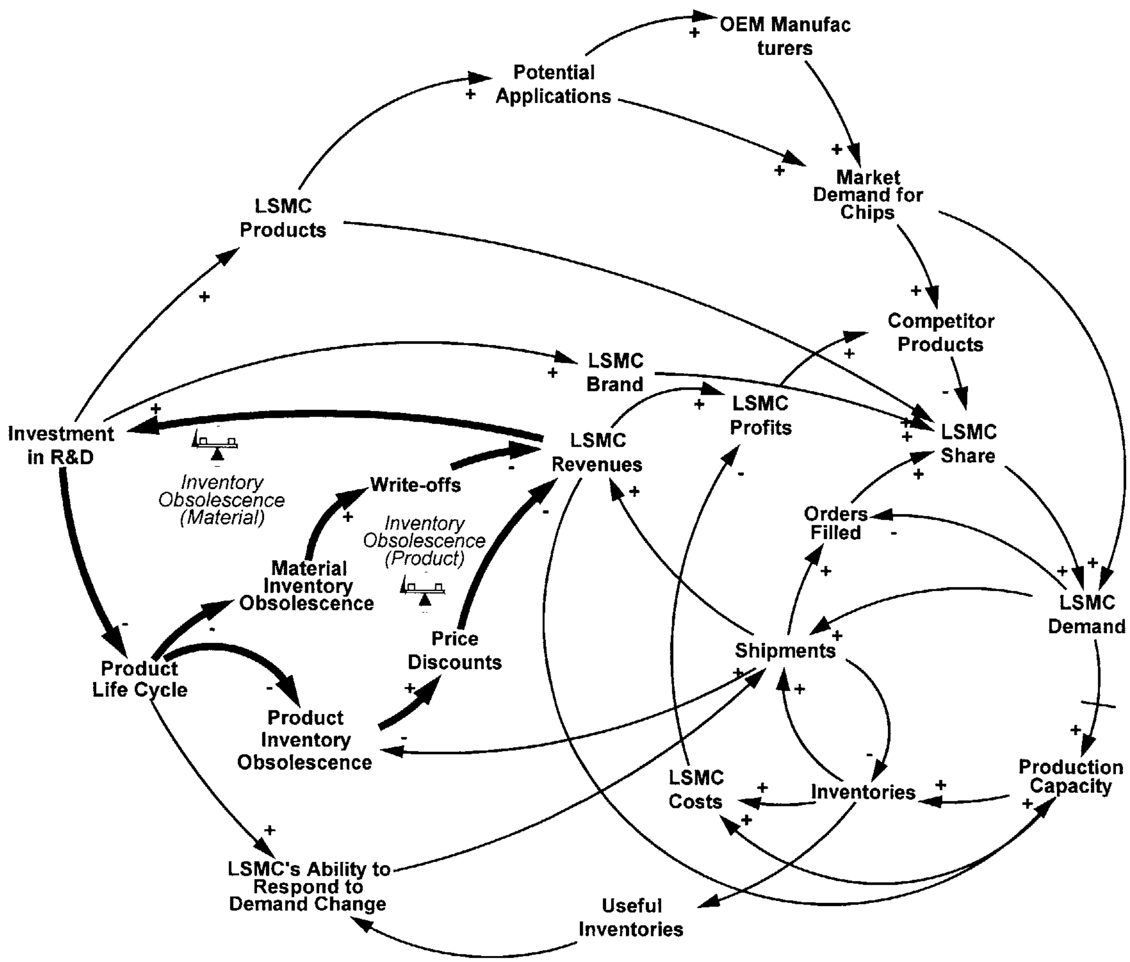

Figure 5.10 Inventory obsolescence

5.10 Ability to respond to demand due to product life cycle

Having the right products and the right capacity becomes harder as the product life cycle decreases. Ability to respond to the demand decreases when the product life decreases. Moreover, new products always have more complex architecture than the previous generations. This complexity leads to more manufacturing time and lead-time and requires more processing time in manufacturing. Figure 5.11 depicts the idea behind this hypothesis. Note that the loop in Figure 5.11 is a balancing loop.

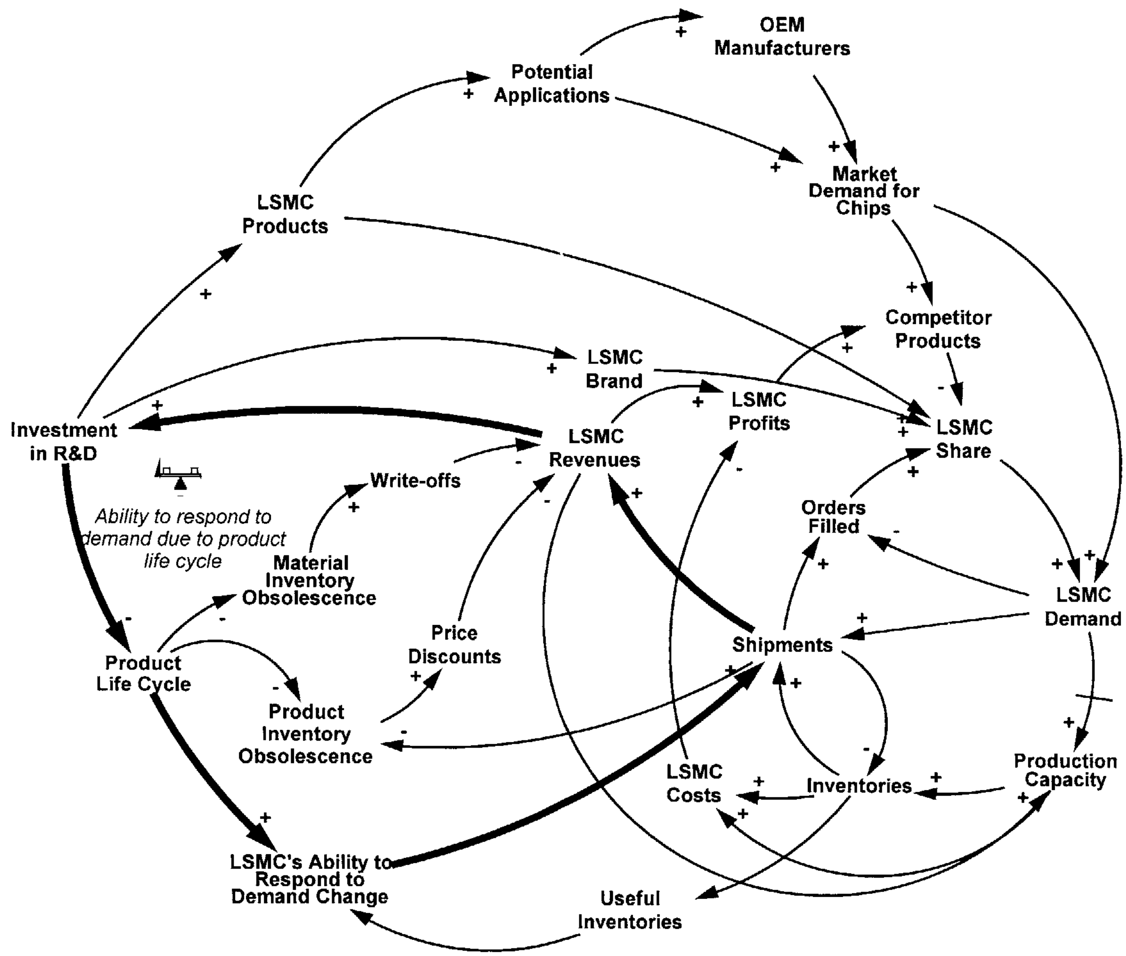

Figure 5.11 Ability to respond to demand due to product life cycle

5.11 Ability to respond to demand due to OEMs' order cancellation

Because short life cycle of LSMC's products, most companies do not want to maintain large inventories of LSMC's products. The unsold products become obsolete faster than they used to. OEMs such as Dell have changed the manufacturing process to Build-To-Order (BTO) instead of build-to-stock. BTO manufacturing permits Dell to operate with virtually no finished goods inventory and only seven days or fewer of supply chain inventory. The hypothesis is captured in the reference mode, OEM's Inventory in Figure 3.10. Dell's BTO strategy puts pressure on their suppliers, including LSMC, to have shorter time allowed for cancellations of its orders which is illustrated in the reference mode, Change in Customer Orders, in Figure 3.4. Figure 5.12 summarizes the hypothesis that LSMC's ability to respond to demand decreases as Dell and other OEMs have more flexibility to cancel orders. The loop in Figure 5.12 is a balancing loop.

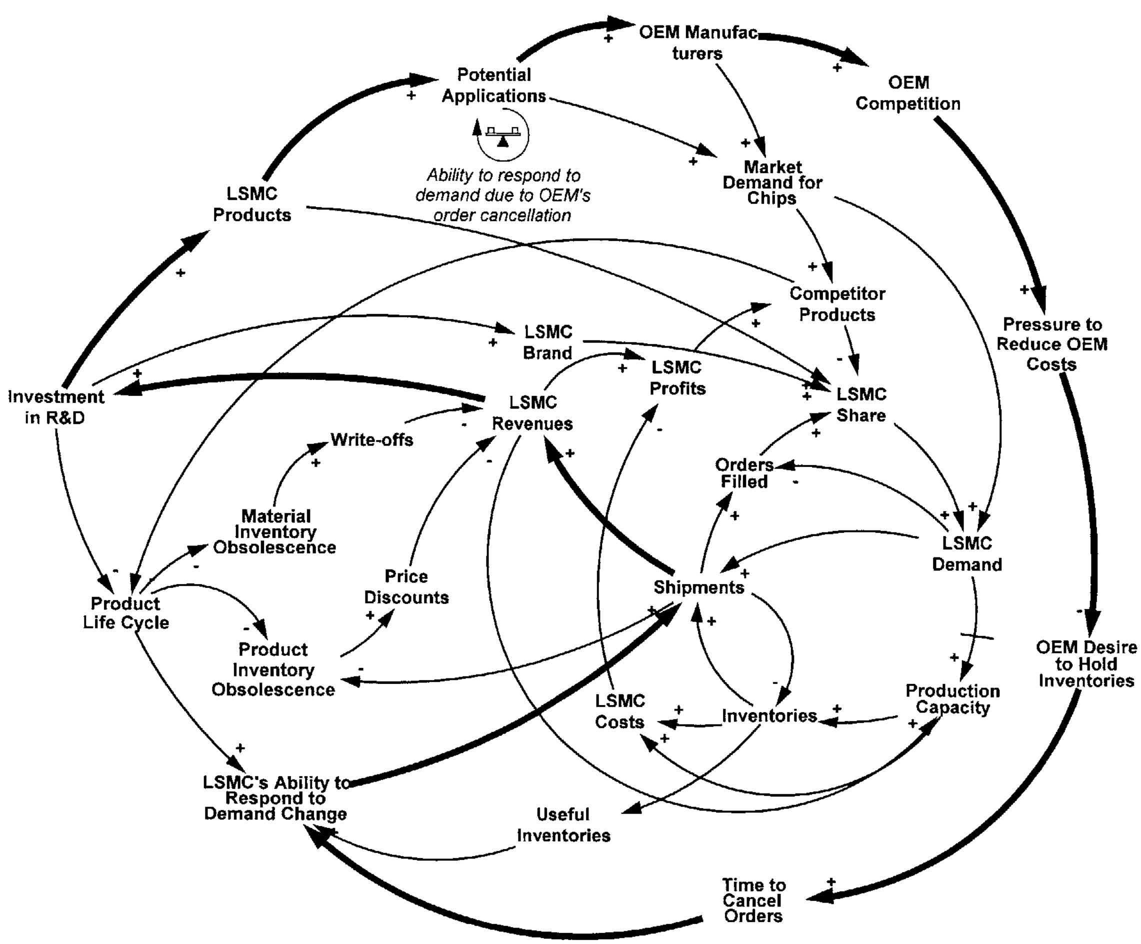

Figure 5.12 Ability to respond to demand due to OEMs' order cancellation

5.12 Market share taken by competitors

This hypothesis continues from the loop "High Profits Induce Competitor Entry" in Figure 5.6. As the PC market grows, the demand for other computer complimentary products also increases. LSMC's competitors have an opportunity to break into the market especially in the low-end market. If LSMC cannot fulfill the demand of this market, competitors may be able to take LSMC's existing and potential market share and they may erode LSMC's revenue as well. Figure 5.13 represents the balancing loop that explains this hypothesis. If the impact of this balancing loop is significant, it may reduce LSMC's products in the market and lead to the slow growth in LSMC's demand which is the fear captured in the reference mode, in Figure 3.2.

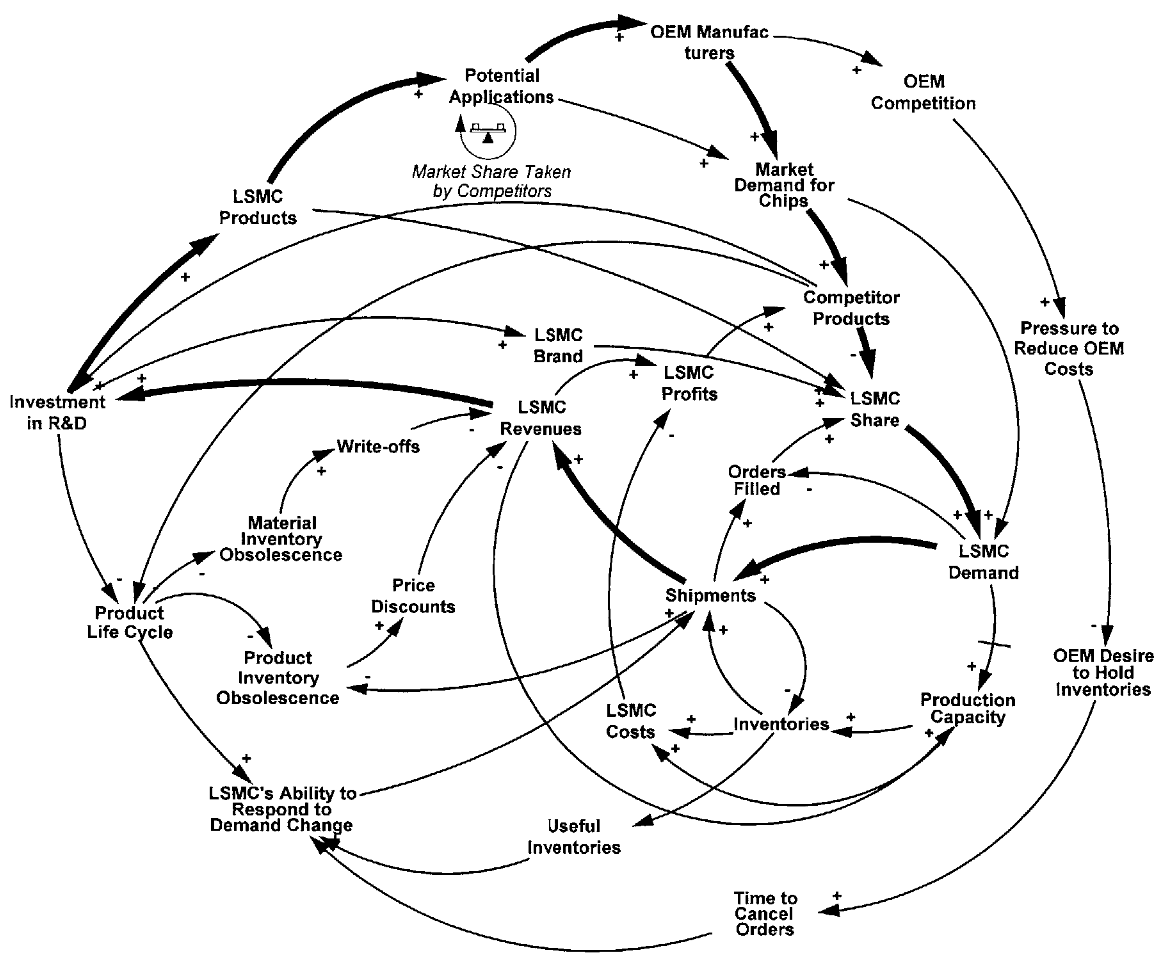

Figure 5.13 Market share taken by competitors

5.13 Competitive response

LSMC is the market leader and wants to stay ahead of its competitors. In order to do so, LSMC needs to invest more in R&D to respond to competitors' new products. As a result, LSMC has to introduce more new products to the market. This hypothesis is presented in the reinforcing loop in Figure 5.14.

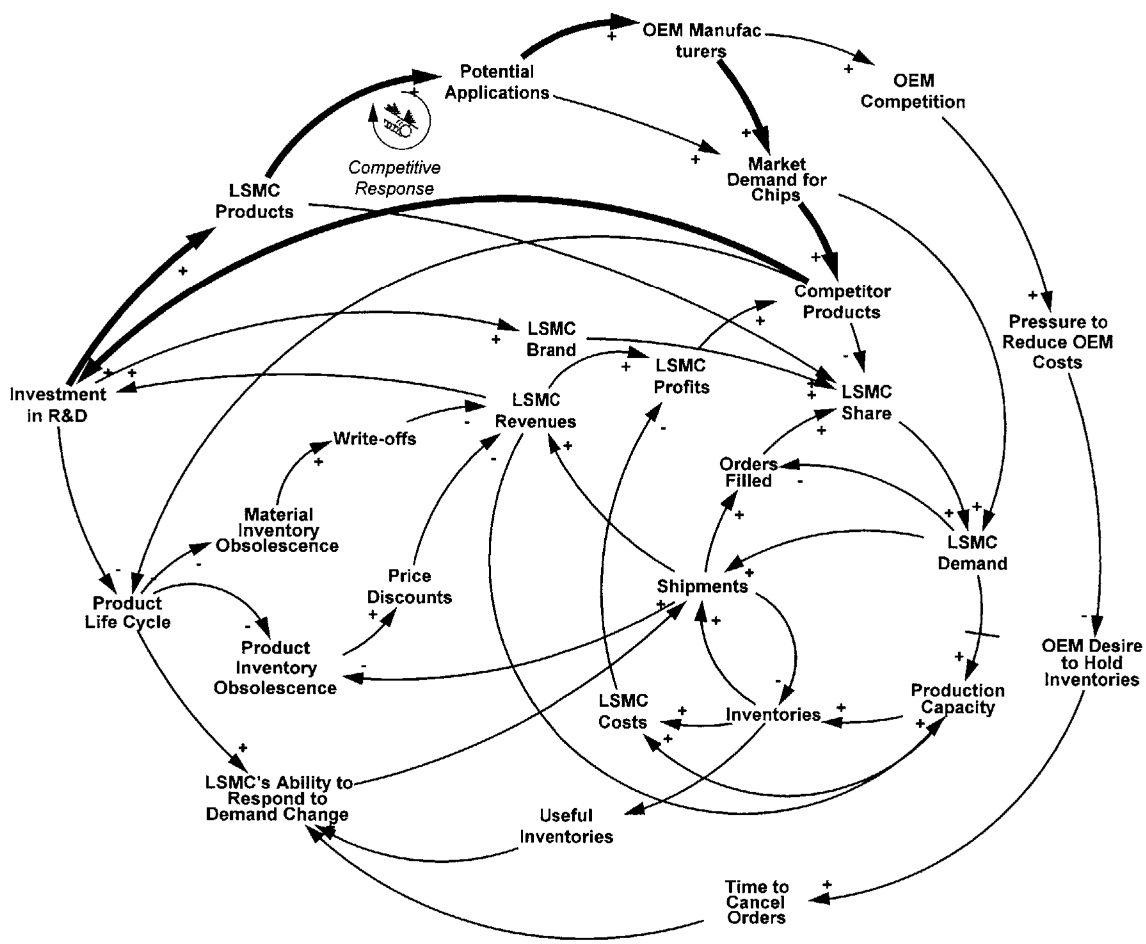

Figure 5.14 Competitive responses

5.14 Competition decreases product life cycle

To compete with other competitors' products, LSMC introduces more new products to the market. However, this strategy decreases product life cycle, which is illustrated in the reference mode, Product Life Cycle in Figure 3.1, and LSMC's ability to respond to the demand changes. Figure 5.15 illustrates the idea behind this hypothesis. Note that this loop in Figure 5.15 is a balancing loop.

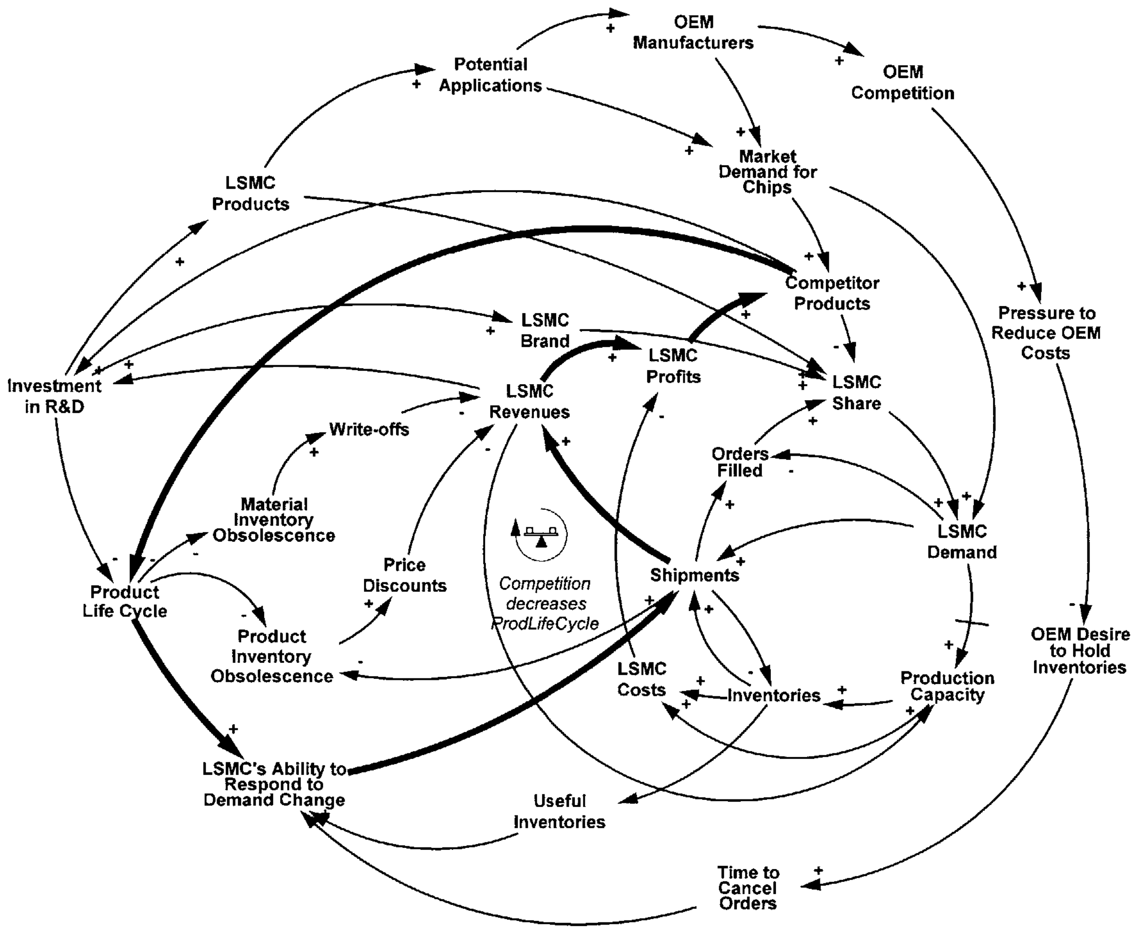

Figure 5.15 Competitive decreases product life cycle

5.15 No water-falling

In the past, LSMC used a technique called "water-falling": introducing new products in the high-end market, discounting the existing products and pushing the existing products to the lower segments. Major investment in R&D leads to breakthrough technologies and OEM competition is also driving computer prices down. To accommodate customer needs and to compete in the industry, LSMC has constantly introduced new products at a faster rate and water-fallen the products faster than it used to. Before LSMC could fully appreciate the revenue and capitalize on its investment from the new products, it had to introduce a newer product to compete with competitors. In the past few years, the water-falling strategy has no longer been effective. LSMC has changed its strategy by segmenting the market into low end and high end instead of water-falling its products. The Internet has also changed the main use of the PC from a tool for running a huge program and consuming CPU power to a browser device. The incentive to buy a faster PC to run a huge program is quickly evaporating. Instead, the Internet generates exponential growth in the low-end markets for the PC industry. The reinforcing loop in Figure 5.16 displays the idea behind this hypothesis.

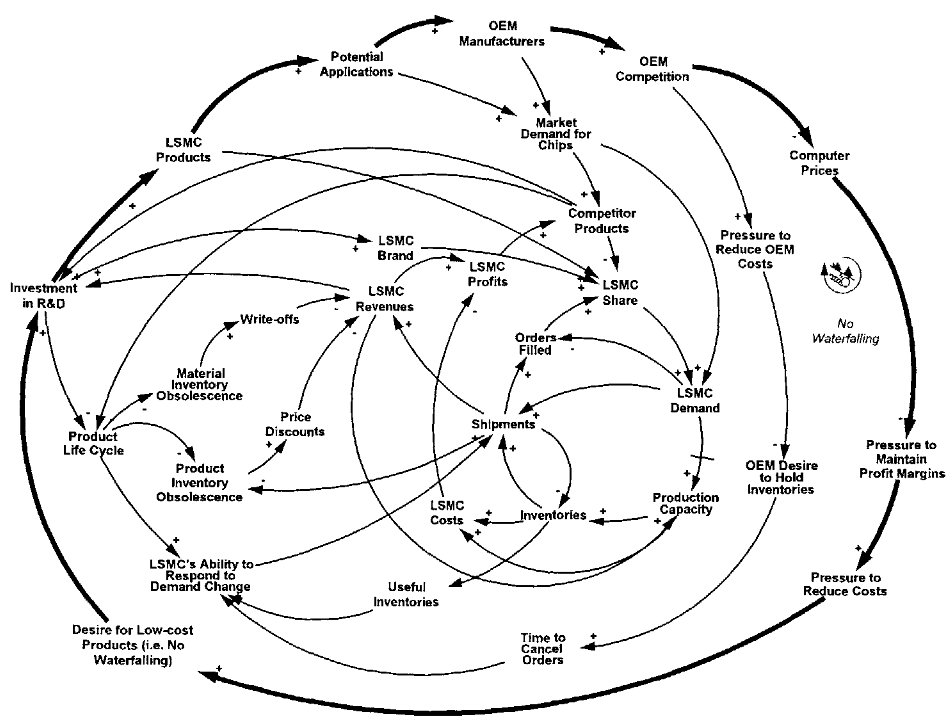

Figure 5.16 No water-falling

5.16 Segmentation increases revenue

In the past, LSMC marketed only two or three unique products at any given time. Because of the fast product life cycle, the water-falling strategy does not work as effectively as it used to. Moreover, there are pressures from both competitors and OEMs to introduce new products. The PC market itself has changed significantly as well. Emergence of the Internet and the Network Computer (NC) targeted primarily at corporate customers and the appearance of the sub-$1000 PC have affected LSMC's business model and pricing strategy.

LSMC's market strategies have changed over the last several years. To respond to those trends, LSMC has segmented the market by introducing more varieties of products at the same time with different clock speeds, cache sizes and architectures. LSMC launched HighA in the server market and other high-end markets, which have high profit margins. LSMC also introduced LowB for low-cost PC markets. Even though LowB has a low margin, the low-cost PC market is much larger in volume compared to the server market. The segmentation policy was introduced to substitute for the water-falling policy, discussed in section 5.16. This hypothesis is presented in the balancing loop in Figure 5.17

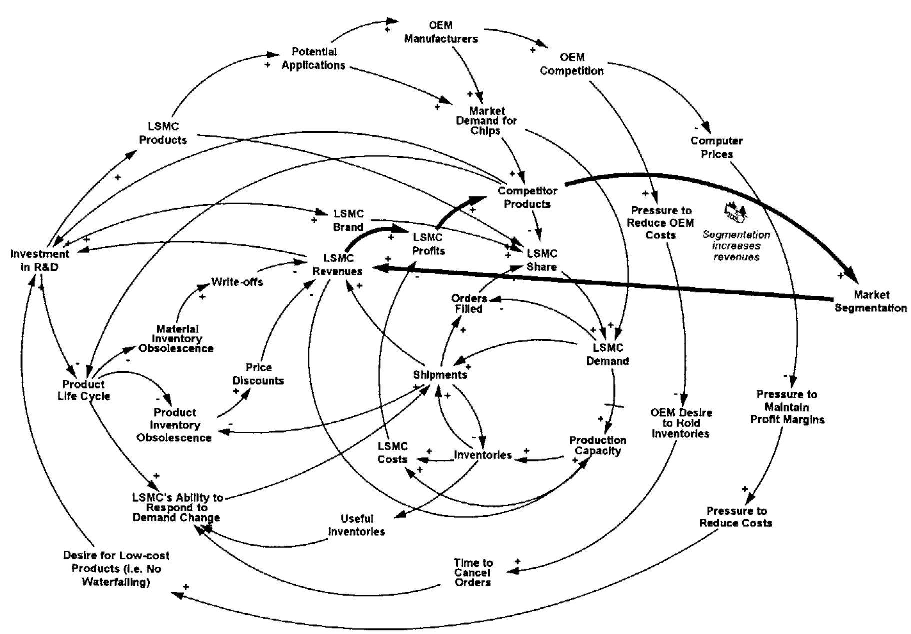

Figure 5.17 Segmentation increases revenue

5.17 Segmentation deceases product life cycle

As discussed in section 3.2.1, LSMC's product life cycle is decreasing. By segmenting the market (, for example LSMC introduced LowB in low-end market and HighA in high-end market,) LSMC is able to prolong the life cycle of its products. This hypothesis is presented in the balancing loop in Figure 5.18.

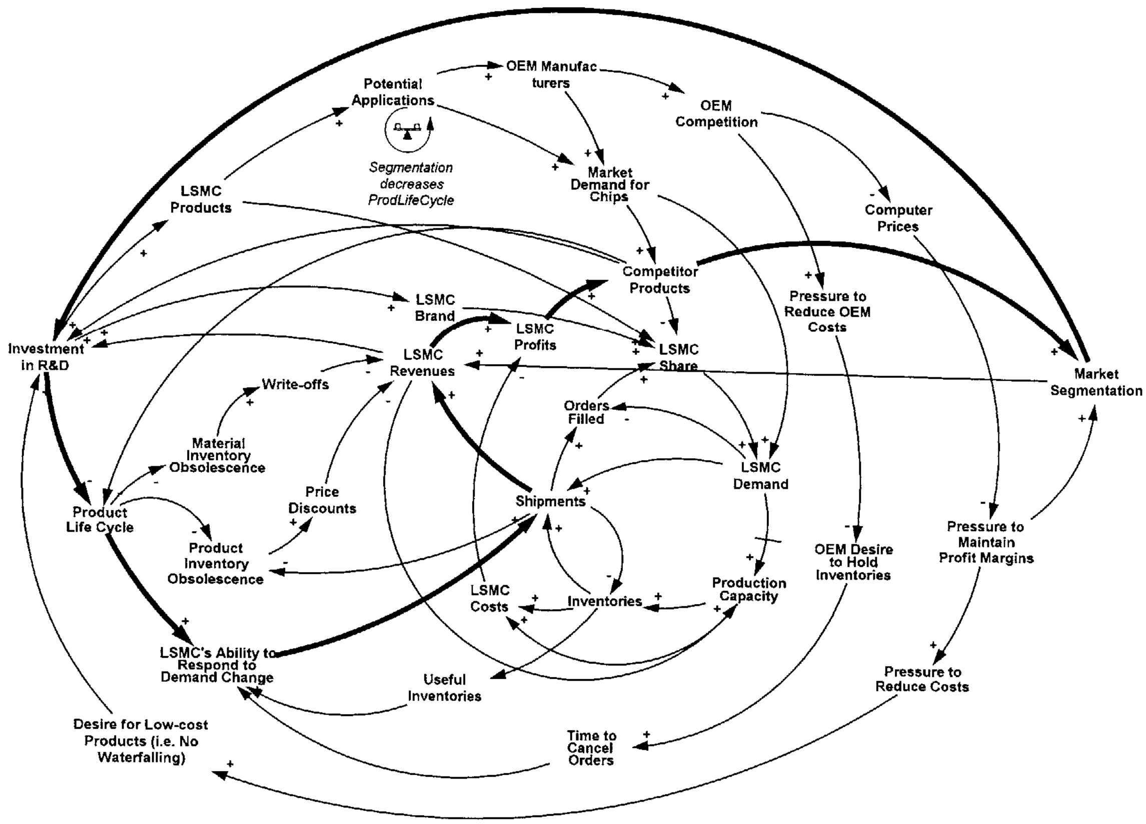

Figure 5.18 Segmentation deceases product life cycle

5.18 Segmentation decreases product flexibility

By segmenting the market, LSMC has to produce and carry a greater variety of its products, which in turn decreases its capacity flexibility and its ability to respond to demand. Figure 5.19 summarizes the hypothesis that the segmentation policy decreases product flexibility. Note that the loop in Figure 5.19 is a balancing loop.

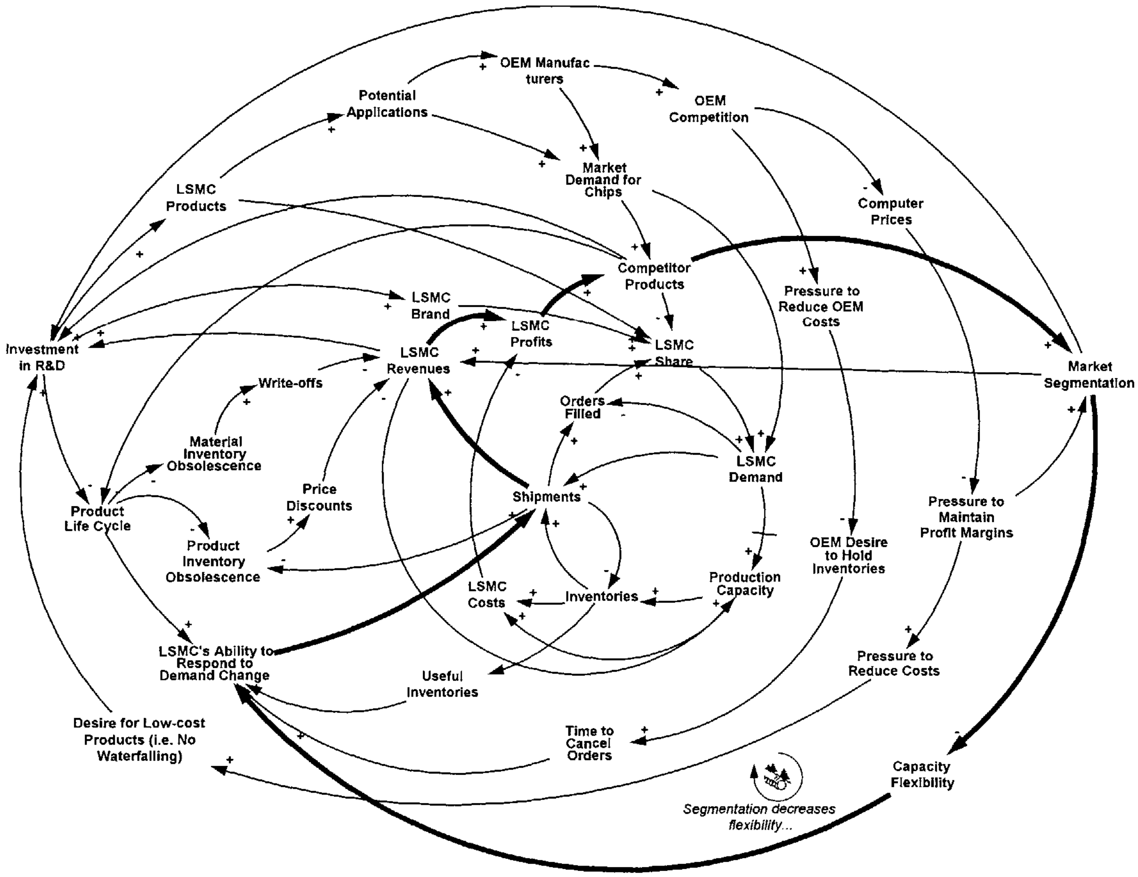

Figure 5.19 Segmentation Decrease Product Flexibility

The casual loop diagram can be categorized in several areas. Separating the diagram to several areas will help identify which area may cause the problem or which area should be focused to solve the problem. Market and OEM are external factors which LSMC may not be able to influence. R&D, Plant and Inventory Management are internal factors which LSMC should have an ability to control those factors.

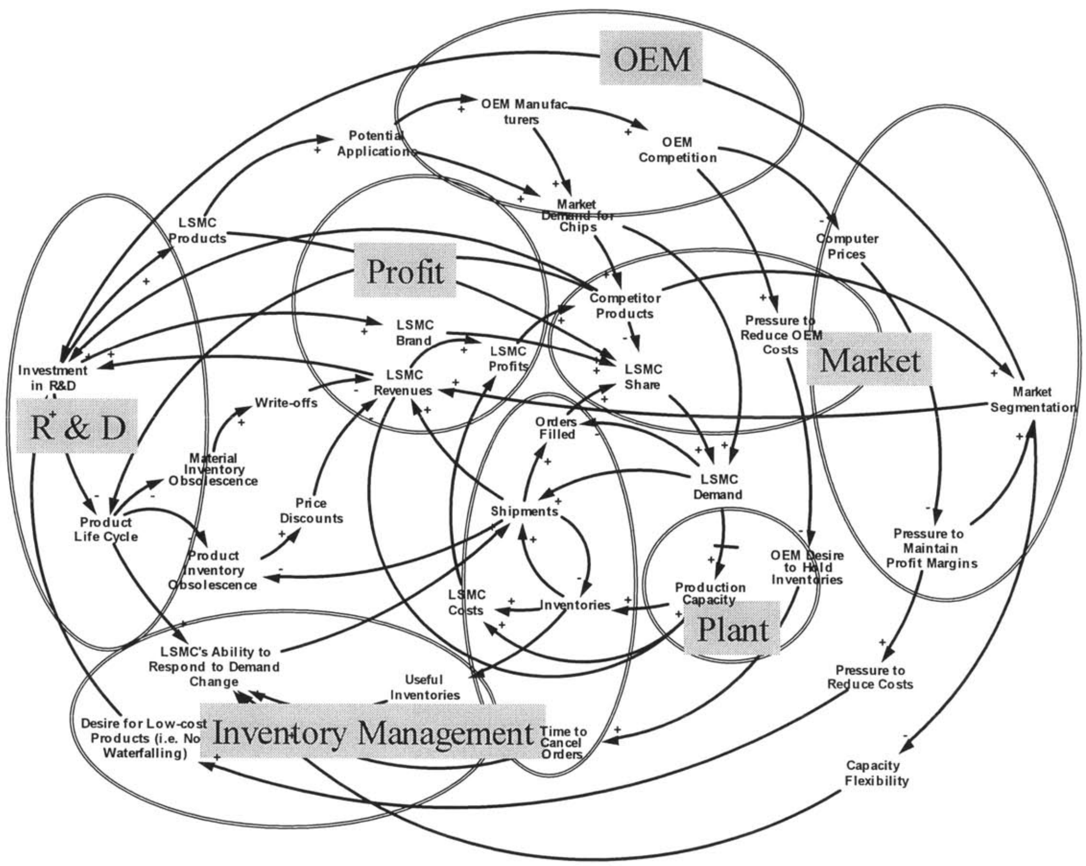

Figure 5.20 Causal Loop Diagram Grouped by Operations

5.19 Momentum Policy and Causal Loop Diagram Mapping

From the momentum policies in Section 4.2, these policies can be categorized in terms of duration of planning, e.g., long-term and short-term planning (see Figure 5.21). Most of the momentum policies related to production tend to be short-term solutions. The momentum policies related to demand tend to be long-term solutions.

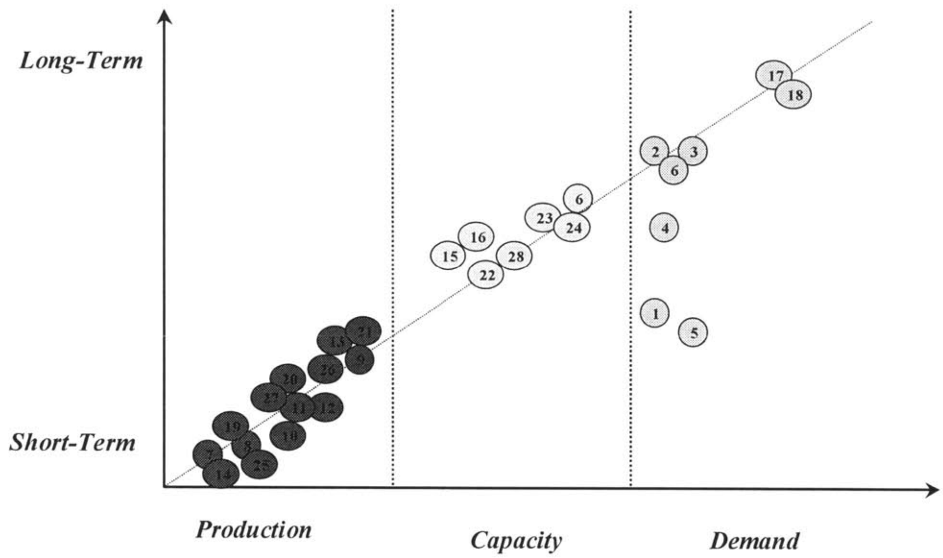

Figure 5.21 Momentum Policy Mapping Diagram

To understand the impact of the momentum policies on LSMC's supply chain problem, the momentum policies are mapped to the causal loop diagram. In Figure 5.22, momentum policy # 1 – SLM, which impacts both the demand and the inventories, is mapped to the variables, LSMC Demand and Useful Inventories in the causal loop diagram.

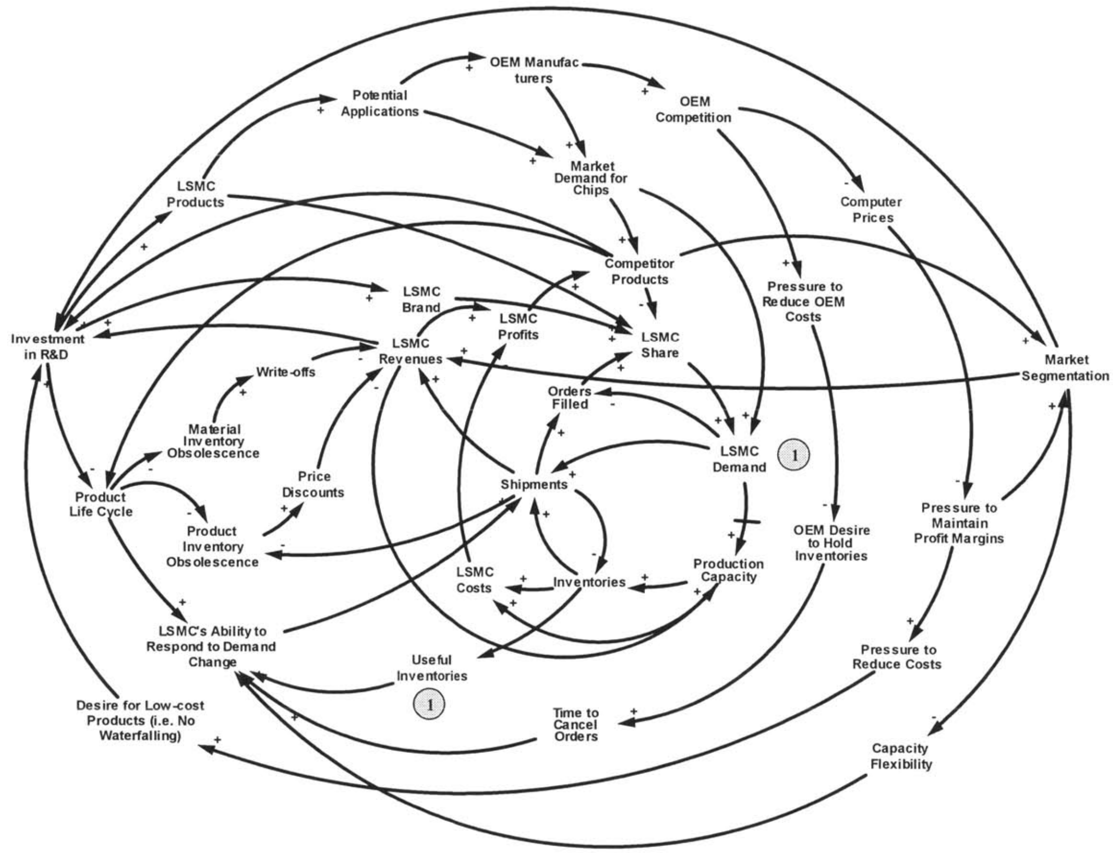

Figure 5.22 MP#1 - SLM policy on the causal loop diagram.

Momentum policy #2 attempts to increase market share by offering the best performance to beat the competition. As a result, LSMC invests more in R&D to improve the product performance. The policy is mapped to the variables, LSMC Share and Investment in R&D in the causal loop diagram in Figure 5.23.

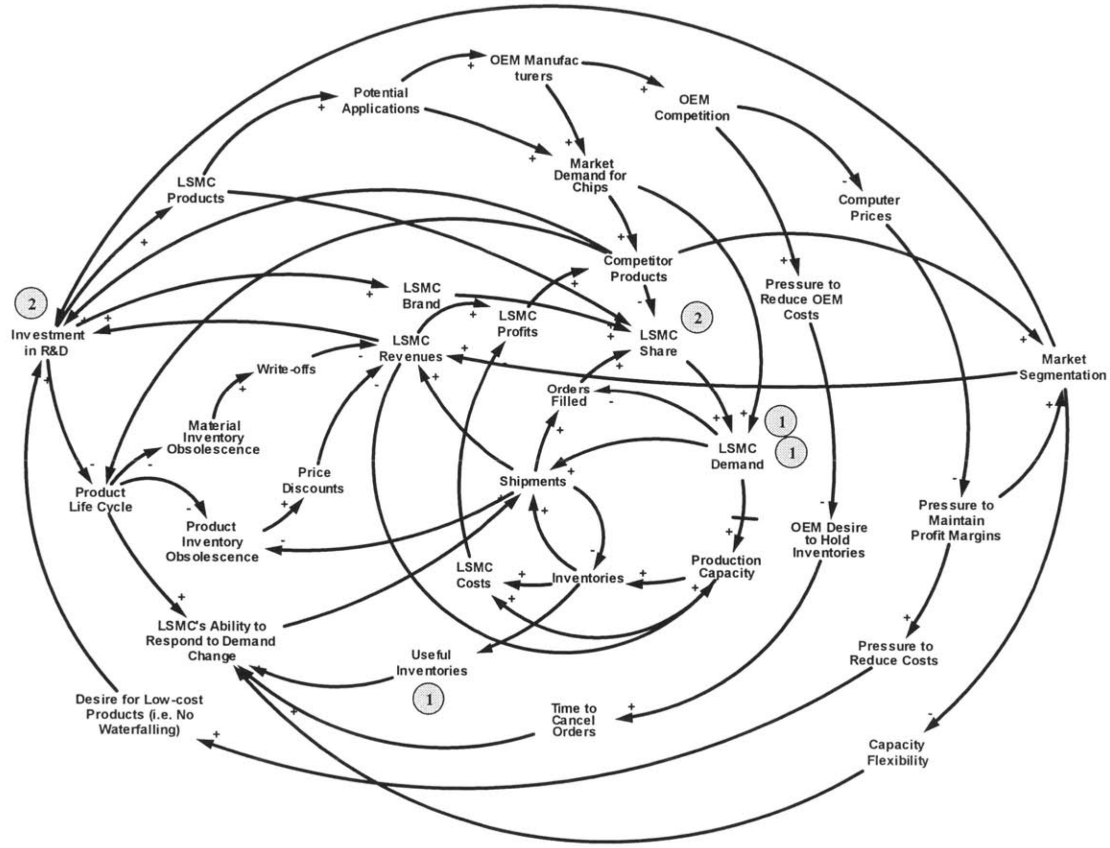

Figure 5.23 MP#2 - Competitive Response policy on the causal loop diagram.

Following the same approach, the rest of the momentum policies can be mapped to the causal loop diagram as shown in Figure 5.24. Figure 5.24 illustrates that most of the momentum policies are mapped to the variable, Production Capacity.

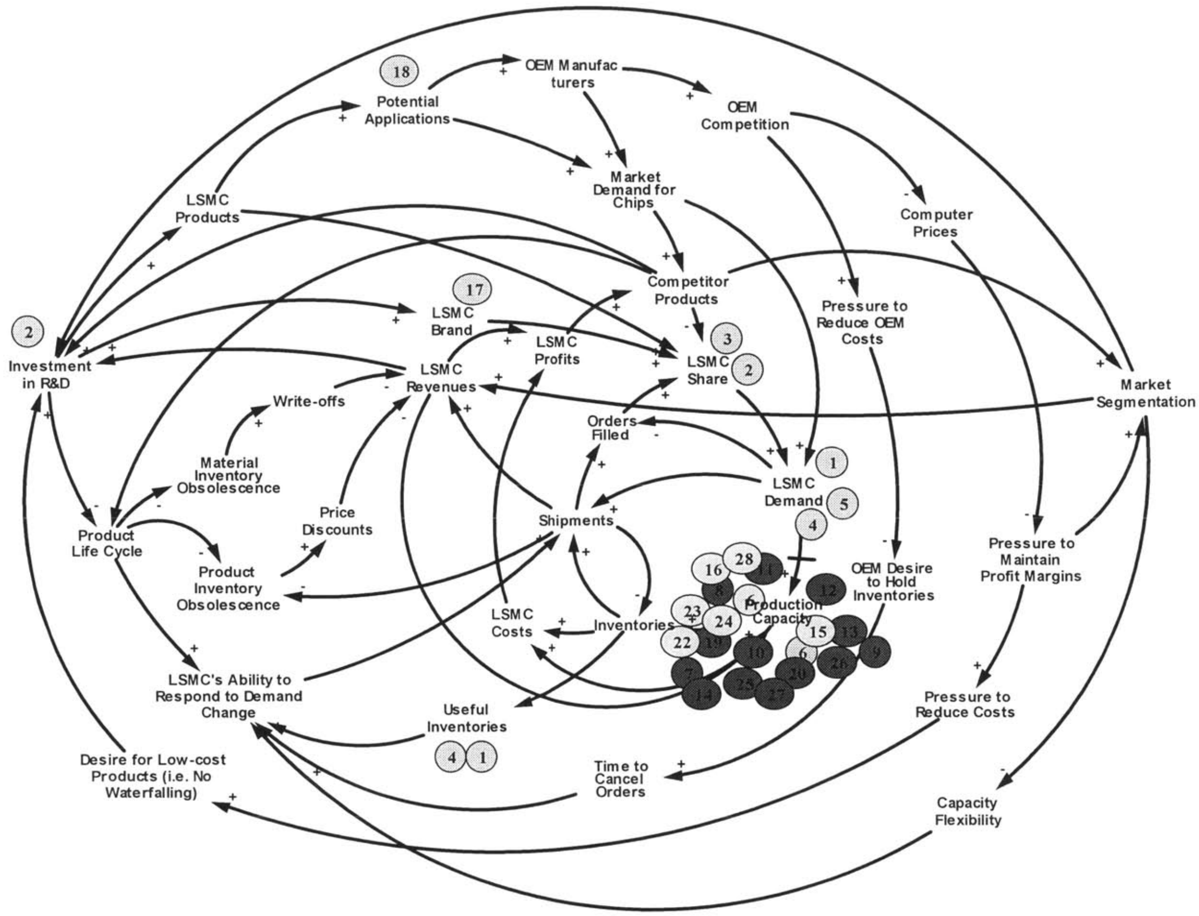

Figure 5.24 All the momentum polices mapped on the causal loop diagram.

The concentration of the momentum policies around Production Capacity indicates that the participants are very concerned about the production capacity and attempt to counter the short-term problems by issuing the policies that involve Production Capacity. LSMC could broaden the view to solve its problems. For example, from the causal loop diagram in section 5.7, Producing the right products keeps LSMC growing, the problems in Production Capacity could come from the upstream such as Inventory Management area (see Figure 5.20), LSMC may be able to counter problems by generating policies in Shipments and Orders Filled areas.

Next step is to choose which area of the causal loop diagram that should be modeled. Because LSMC's supply chain is a complex network, it would be difficult to create the model that covers the entire causal diagram at once. Furthermore, insights may arise from the model that involved only a small section of the causal loop diagram. It is reasonable to model the loop or loops that involve Production Capacity which a number of participants were very concerned and considering several policies to counter the problems. The scope of the model should be involved other area as well. One of the hypotheses is the Inventory Management area (see Figure 5.20) could play a role in the fluctuation in Production Capacity area. So Shipments and Ordered Filled should be in the model. The initial loops that will be modeled are the highlighted loops, shown in Figure 5.25.

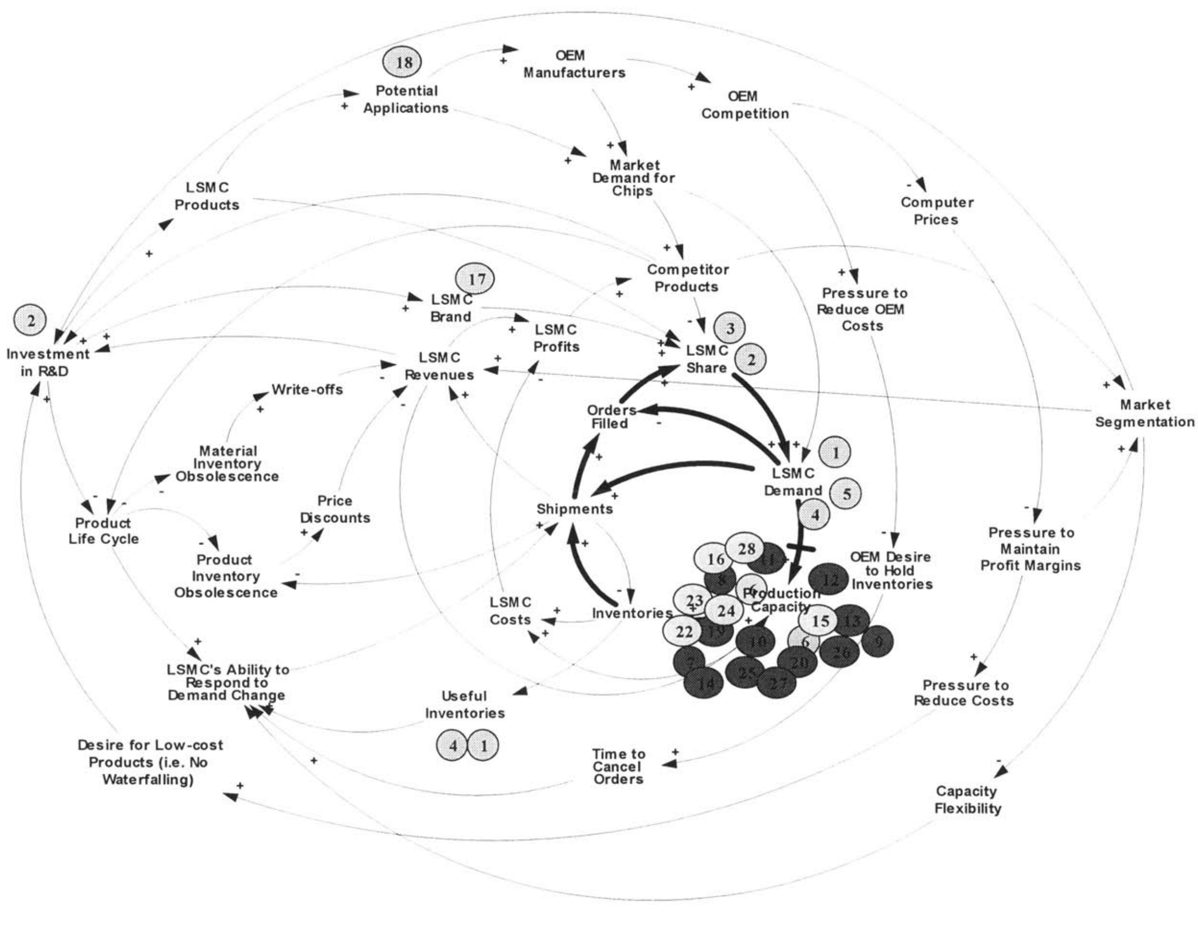

Figure 5.25 The highlighted loops are the focus for initial modeling

Note that the initial model could be chosen from other areas depending on assumptions. The details of the modeling, including simulations and analyses, will be discussed in the next chapter.

Chapter 6 Model Development

The next step of the system dynamics process is modeling. Vensim is the software package that is applied to develop LSMC supply chain model. In system dynamics, the modeling process is often an extensive and tiresome process. System dynamics practitioners attempt to ease and accelerate the process by creating collections of templates or libraries of commonly used components, e.g. Hines' Molecules (Hines, 1997). The model in this thesis is built based upon components from Hines' Molecules and components from Sterman's Business Dynamics (2000). However, those components are generic and they do not capture all the details of LSMC's environment. Therefore, some of those components are modified to fit LSMC supply chain model.

The structure of a model consists of two major components representing the physical environment and the decision rules of the managers who make decisions within the physical environment. Additionally, dynamically realistic models should account for the delays and missing measurement and reporting information.

Based upon the causal loop diagram/momentum policies mapping (see Figure 5.25) in Section 5.19, LSMC supply chain model in this chapter will be constructed based upon the loops (see Figure 6.1) that involve Production Capacity which a number of participants considered several momentum policies. Another hypothesis is that Inventory Management area (see Figure 5.20) could play a role in the fluctuation in Production Capacity area (see Figure 5.20). So Shipments and Ordered Filled are included in the initial LSMC supply chain model.

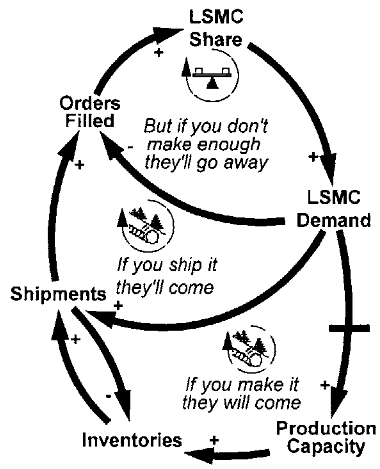

Figure 6.1 Initial Loops for Modeling

6.1 Modeling

This section discusses how each component of LSMC supply chain model is constructed. LSMC supply chain model can be separated into three models:

1) Production
2) Shipment
3) Demand forecast and capacity.

6.1.1 Production Model

From the causal loop diagram in Figure 6.1, it can be seen that LSMC's demand drives the production and the production builds up inventories for distribution. The production model in this section captures the idea of these two links which is represented in Figure 6.2.

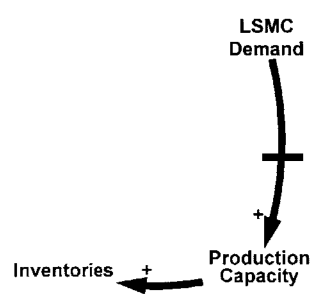

Figure 6.2 Production Model Causal Links

Figure 6.3 presents LSMC's production diagram. LSMC runs a push-pull manufacturing process and also runs the production by having the pre-assembly as the constraint, but the assembly and test unit and materials are not constraints. At the beginning of the process, a pre-assembly facility pushes to an assembly and test unit. However, finished goods orders pull from the assembly and test unit. Note that there are also two inventory policies:

i) Build to forecast - supplier centric, front end
ii) Build to order - customer plan replenishment.

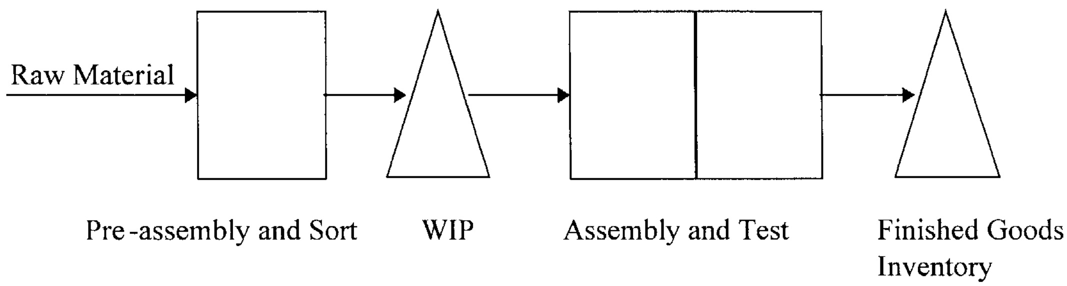

Figure 6.3 LSMC's Production Diagram

To simplify the model, the pre-assembly unit and the sort inventories are aggregated in one stock, called Pre-assembly Inventory, and the assembly and test inventories are also aggregated in one stock, called Assembly Inventory. LSMC's production model was constructed based on Production Starts model (see Figure 6.4) from Sterman's Business Dynamics (2000), Section 18.1.3.

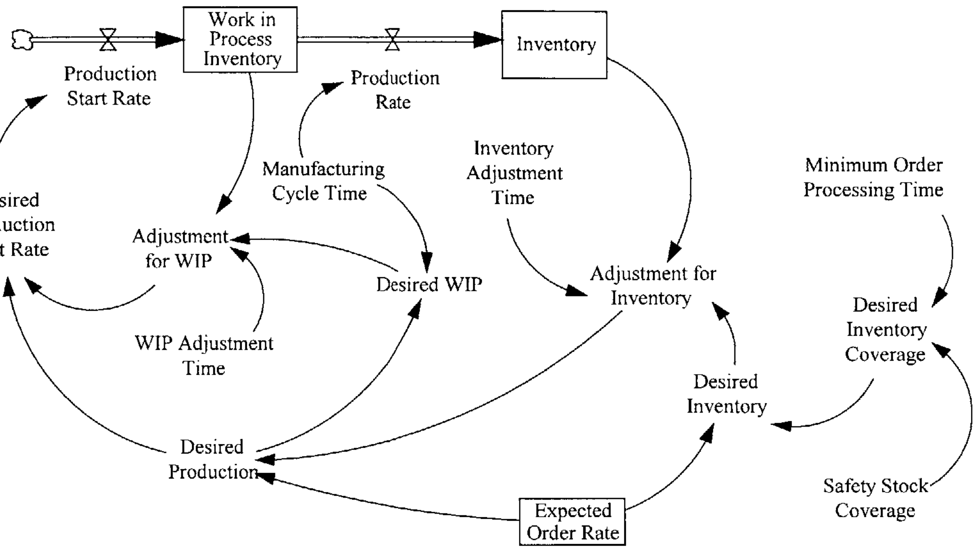

Figure 6.4 Sterman's Production Starts

Because Sterman's Production Starts model is a generic model and it captures only one step production, the model needs to be customized to fit LSMC's environment. First, Production Starts model's variable names are modified to match LSMC's terminology, and other parameters, e.g. yields and unit conversion, are added to the model. Second, to capture both Pre-assembly Inventory and Assembly Inventory in LSMC's production process, Working in Process Inventory stock of Production Starts model needs to be dividing into Pre-assembly Inventory stock and Assembly Inventory stock. LSMC runs a push process from the pre-assembly process to the assembly process and runs a pull process from the assembly process to the packaging process where the finished goods come out. Figure 6.5 illustrates LSMC's production model. The Expected Channel Demand for LSMC Products is a smooth function of Channel Demand for LSMC Products.

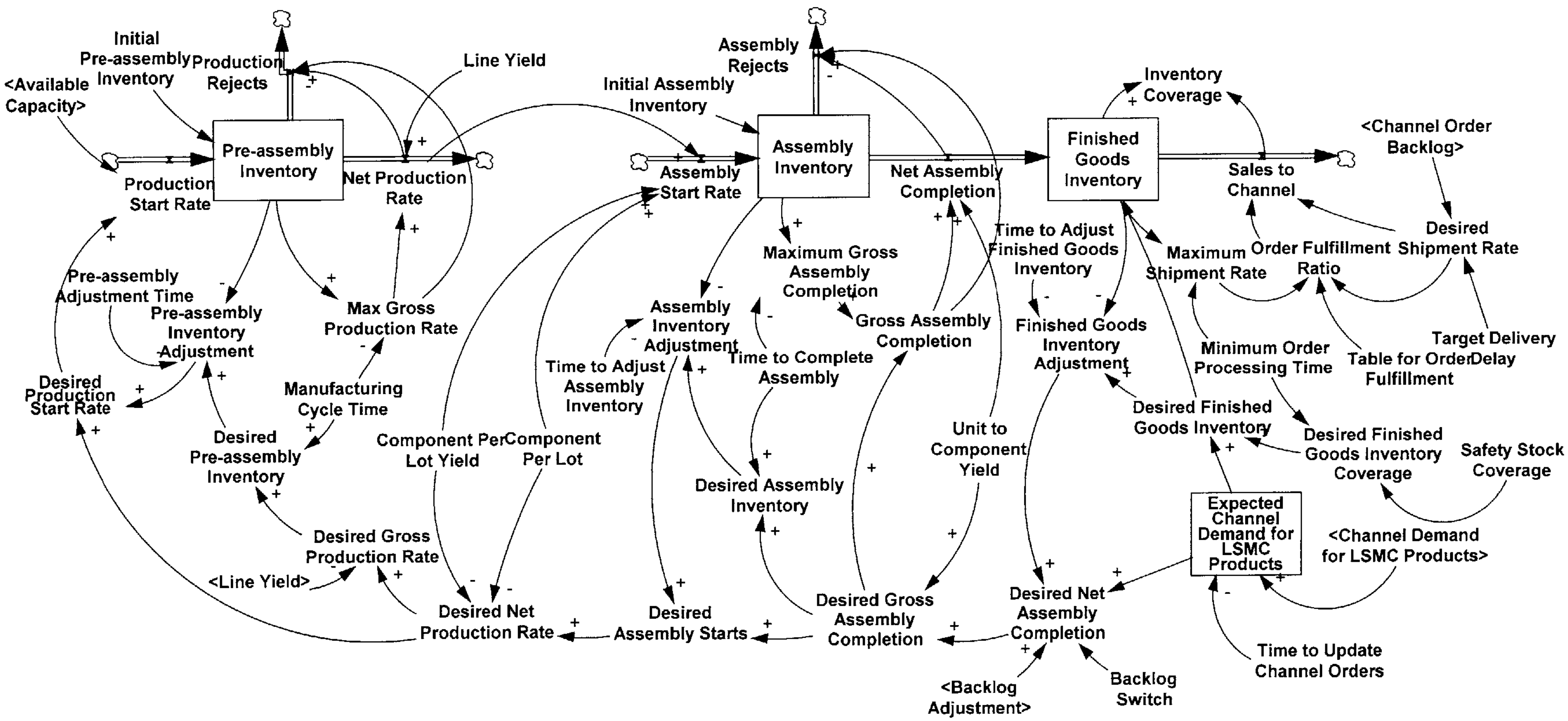

Figure 6.5 Production Model

6.1.2 Shipment Model

LSMC's shipment model comprises of two sub-models.

1) Inventory, Backlog and Shipping. This sub-model represents the idea of the links of Inventories, Shipments Orders Filled (see Figure 6.6) in the causal loop diagram in Figure 6.1.

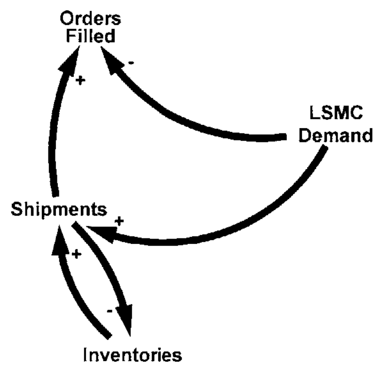

Figure 6.6 Inventory, Backlog and Shipping Causal Links

The sub-model is created based on Inventory, Backlog and Shipping molecule from Hines' Molecules (see Hines (1997)) and Order Fulfillment model from Sterman's Business Dynamics (2000), Section 18.1.1. From the finished goods inventory, products are shipped to OEMs and other customers. In practice, LSMC cannot deliver the products immediately and it needs to have a backlog of unfilled orders, i.e., a stock that accumulates the discrepancy between Sales to Channel and Channel Demand for LSMC Products. Figure 6.7 illustrates the Inventory, Backlog and Shipping sub-model.

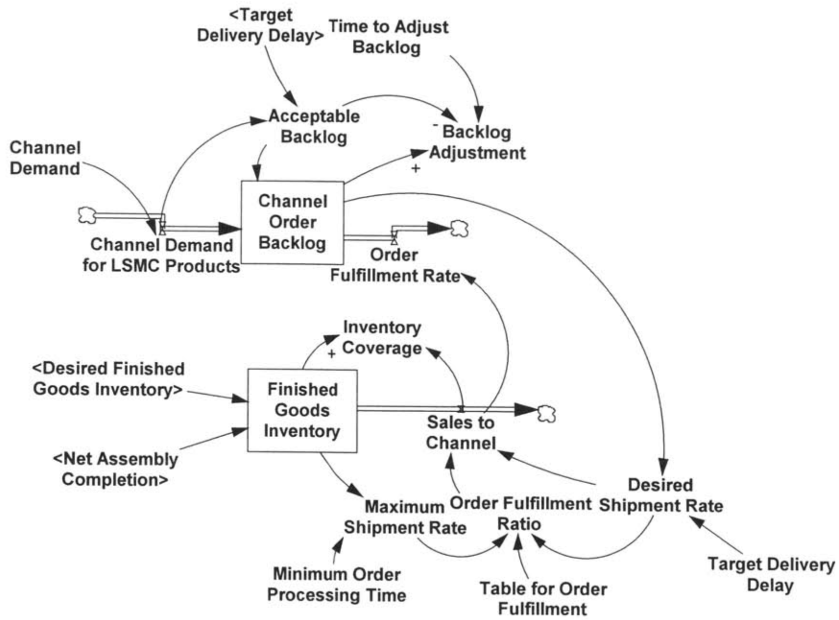

Figure 6.7 Inventory, Backlog and Shipping Sub-model

LSMC's Orders Filled depends on its shipment capability, which is a function of the ratio of Maximum Shipment Rate to Desired Shipment Rate. Figure 6.8 illustrates the Table of Order Fulfillment. When the ratio is less than one, LSMC ships its products as fast as its Desired Shipment Rate. However, when the ratio is greater than one, LSMC can ship only what it has in the Finished Goods Inventory. Note that the table function in Figure 6.8 is also equivalent to Min function in Vensim.

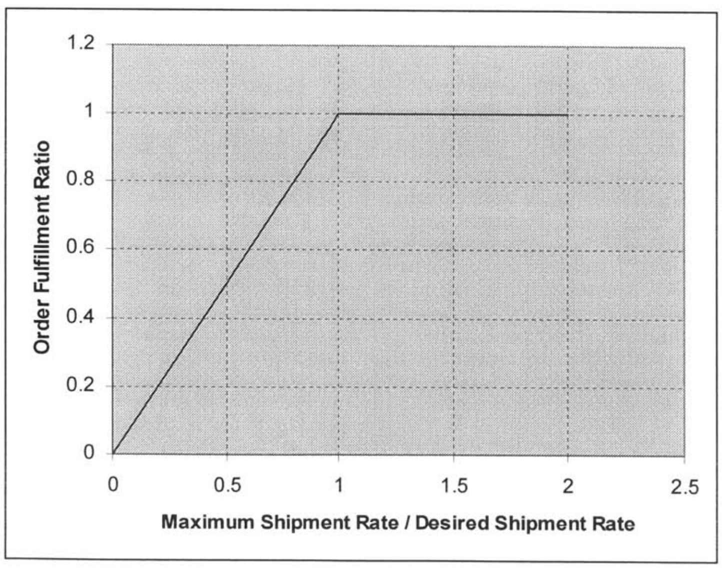

Figure 6.8 Table for Order Fulfillment

2) Market Share. This sub-model represents the link from Order Filled to LSMC Share and the link from LSMC Share to LSMC Demand.

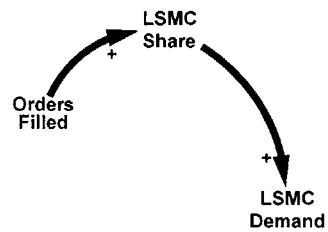

Figure 6.9 Market Share Causal Link

The sub-model is created based on Product Attractiveness molecule from Hines' Molecules (see Hines (1997)). LSMC's demand is driven by its market share and the market share is driven by LSMC's Attractiveness which is determined by how LSMC can fulfill its customer orders.

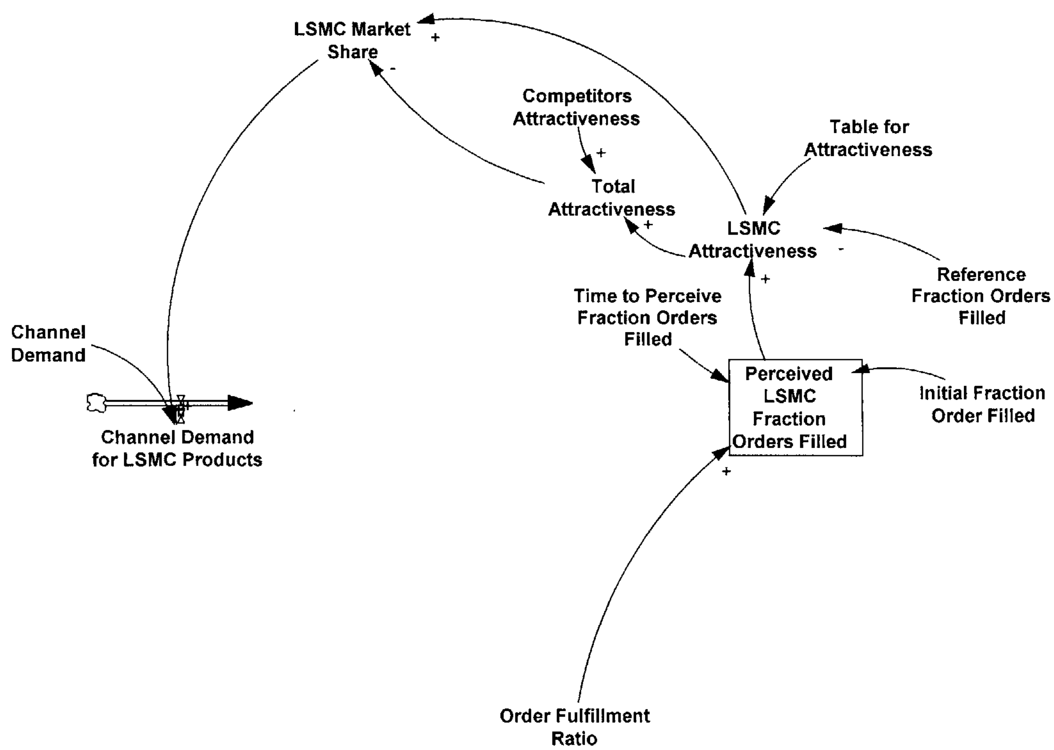

Figure 6.10 Market Share Sub-model

Figure 6.11 describes the Table for Attractiveness. The curve of the table can be divided into three sections:

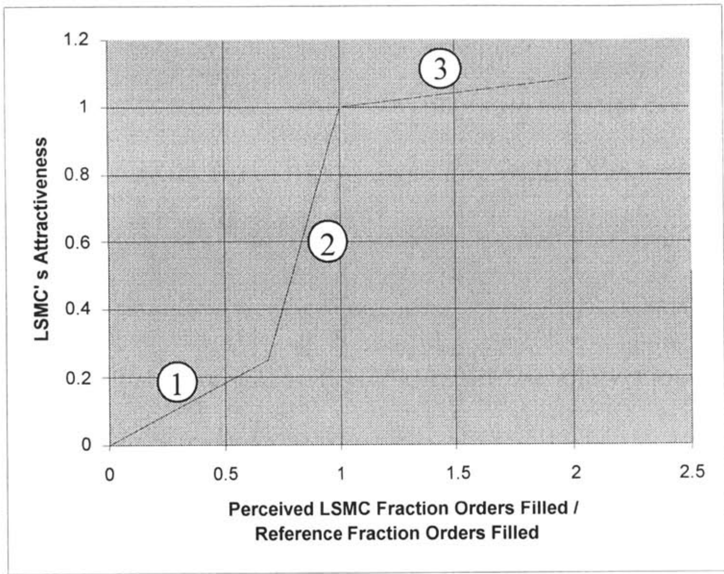

Figure 6.11 Table for Attractiveness

1) When the ratio of Perceived LSMC Fraction Orders Filled to Reference Fraction Orders Filled is small, LSMC may gain a small fraction of its attractiveness if it is able to fill the customers' orders, and it may lose a small fraction of its attractiveness if it is unable to fill the customers' orders.

2) When the ratio is medium, LSMC's orders filled has more impact on its customers. The slope of this range is much more steep than the slope of the low-end and high-end. The steep slope implies that if LSMC can fill its customers' orders, its attractiveness increases rapidly and if LSMC cannot fill its customers' orders, its attractiveness decreases sharply as well.

3) When the ratio is large, LSMC's Attractiveness is already high. Whether LSMC can or cannot fill its orders, the perception of its attractiveness does not change much.

Figure 6.12 illustrates LSMC's shipment model which combines Inventory, Backlog and Shipping sub-model and Market Share sub-model.

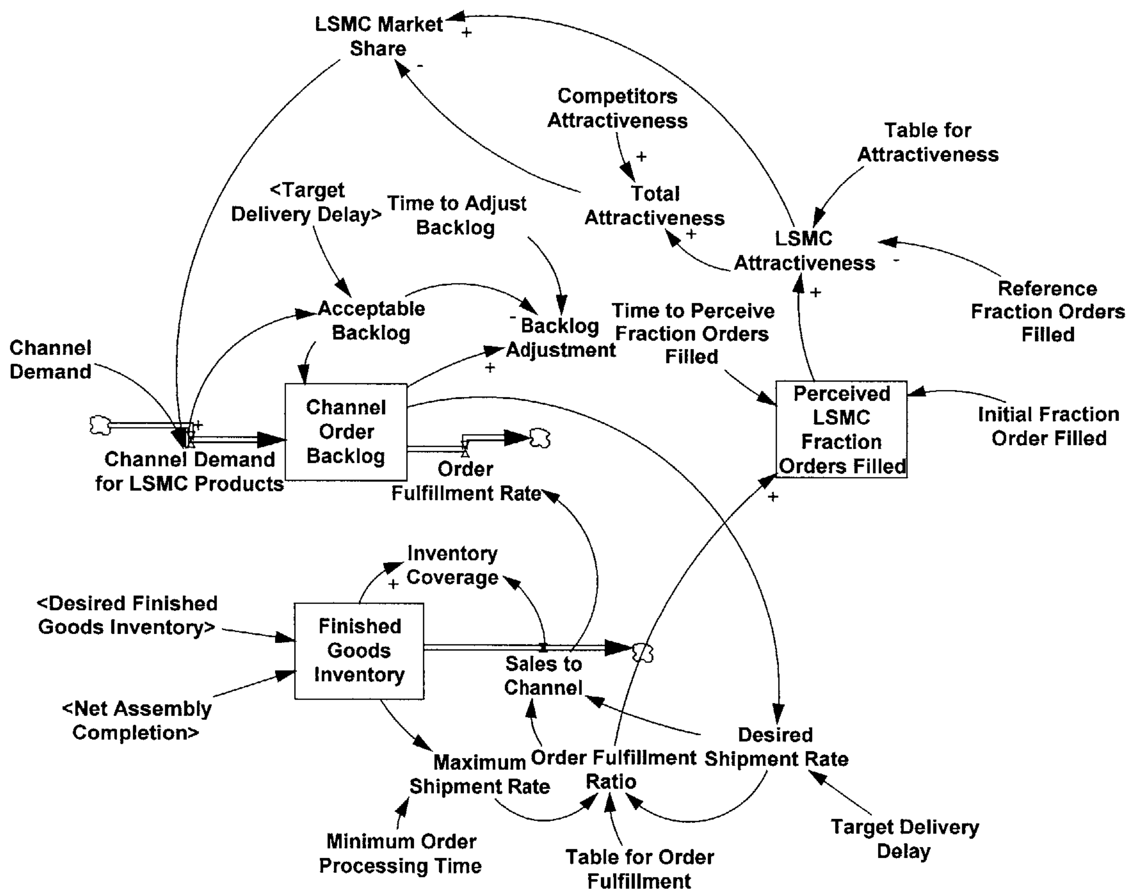

Figure 6.12 Shipment Model

6.1.3 Demand Forecast and Capacity Model

LSMC's demand forecast and capacity model represents the idea of the link from LSMC Demand to Production Capacity in the causal loop diagram in Figure 6.1. The model consists of two sub-models:

1) Demand forecast consisting of:

i) Historical Demand, which is a smooth function with the time constant, Time Horizon for Historical Demand

ii) Perceived Present Demand, which is also a smooth function with the time constant, Time to Perceive the Present Demand.

The variable, Forecast Demand then is calculated from the Historical Demand and Perceived Present demand. The variable, Forecast Demand, with adjustment of anticipated yields projects what LSMC may need, i.e. Indicated Capacity.

2) Capacity, which is determined from:

i) Indicated Capacity

ii) Capacity Acquisition, an estimate how fast LSMC can build a pre-assembly facility.

iii) Capacity Obsolescence, an estimate of an average life expectancy of a pre-assembly facility.

The demand forecast and capacity model is formulated based on the Capacity Ordering molecule from Hines' Molecules (see Hines (1997)) and Demand Forecasting model from Sterman's Business Dynamics (2000), Section 18.1.4. Figure 6.13 represents LSMC's demand forecast and capacity model.

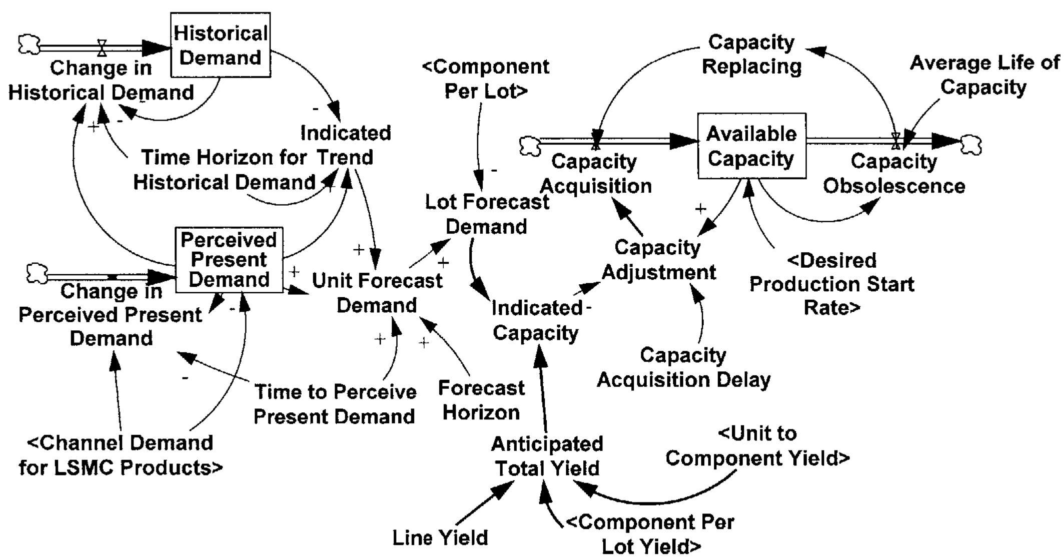

Figure 6.13 Demand Forecast and Capacity Model

Three LSMC's models which are 1) Production, 2) Shipment and 3) Demand Forecast and Capacity, compose LSMC supply chain model. The details including equations and parameters of the model and sub-models are described in Appendix C. The next step is to simulate and analyze LSMC supply chain model. Chapter 7 presents details of model simulations and analysis that lead to insightful information about LSMC supply chain model.

Chapter 7 Model Analysis

LSMC supply chain model was formulated as a system of nonlinear differential equations. The model is large and complicated and there is no algebraic solution. To analyze LSMC supply chain model and to study its dynamic behaviors, several techniques including, simulations, eigenvalue analysis and loop knockout are applied in this chapter.

7.1 Background

Since system dynamics was introduced by Jay W. Forrester in 1956, most system dynamics practitioners have relied heavily on numerical simulations and their intuitions for understanding and analyzing models. System dynamics still has a limited number of tools and techniques for understanding the behavior of very large and complex models such as social and business systems. In recent years, a number of system dynamics practitioners have researched and published studies of alternative techniques such as loop polarity and loop dominance (Richardson, 1984), eigenvalue elasticity, and feedback link and loop gain (Forrester, 1983 and Kampmann, 1996). System dynamics practitioners can use these tools to understand large system behaviors and to design policies more effectively.

7.2 Simulations

The dynamic behaviors of LSMC supply chain model can be studied through simulations by varying the parameters of the model and also applying various types of inputs to the model. First, the model needs to be placed in equilibrium. At the equilibrium, the model does not generate any dynamic behavior, i.e. nothing changes over time, and it lies at the equilibrium unless otherwise disturbed. Next, the model will be disturbed by various types of inputs such as step function, ramp function and sinusoidal function. The analyses of the dynamic behaviors of such disturbances lead to understanding of the patterns described in Section 3.2 Reference Modes.

7.2.1 Step Response Simulation

From equilibrium, LSMC model is disturbed by a 10% step increase in Channel Demand at the sixth month. The step increase in Channel Demand sends a signal to the production. The production facility responds to the increase in Channel Demand by increasing its production. The attempt to balance production with orders is a negative feedback. There are also a number of delays for updating orders and updating productions. The structure of negative feedback and delays cause the oscillatory behaviors in the production before reaching the steady state. Figure 7.1 illustrates the response behaviors of production inventories including Pre-assembly Inventory, Assembly Inventory and Finished Goods Inventory. The oscillatory behaviors in the production inventories were one of the fears described in Production Inventory reference mode in Section 3.2.9 and one of the problem statements in Section 3.3.

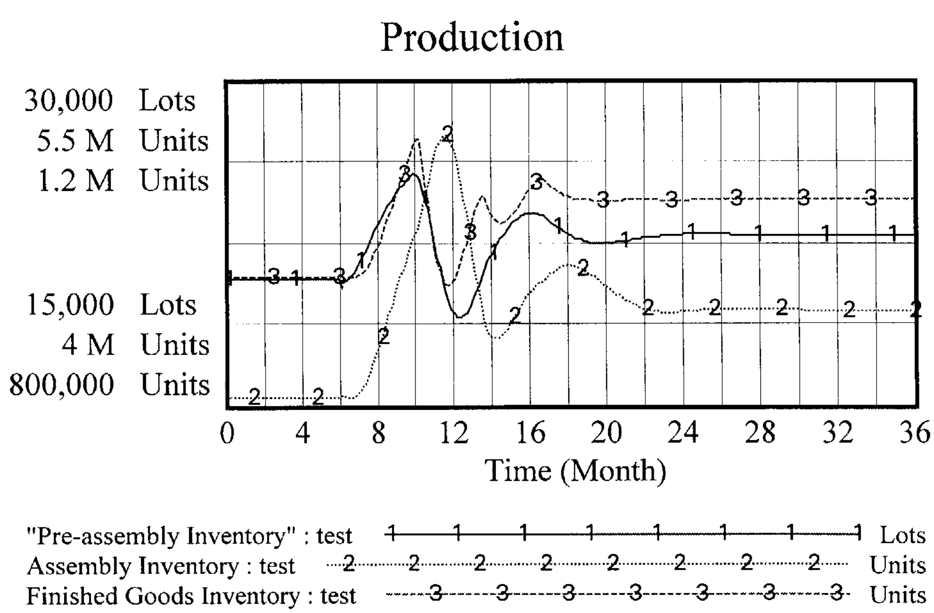

Figure 7.1 Step Response of the Channel Demand for Product Inventories

To meet the increase of the demand and the production, LSMC also expand its capacity. However, the oscillation in production also causes the oscillation in the capacity. Figure 7.2 illustrates the oscillatory behavior and increase in Available Capacity before reaching to a steady state. The capacity fluctuation is also one the reference modes (see Actual Capacity Relative to Desired Capacity in Section 3.2.2) and one of the problem statements in Section 3.3. Sections 7.3 and 7.5 discuss the causes of the oscillations.

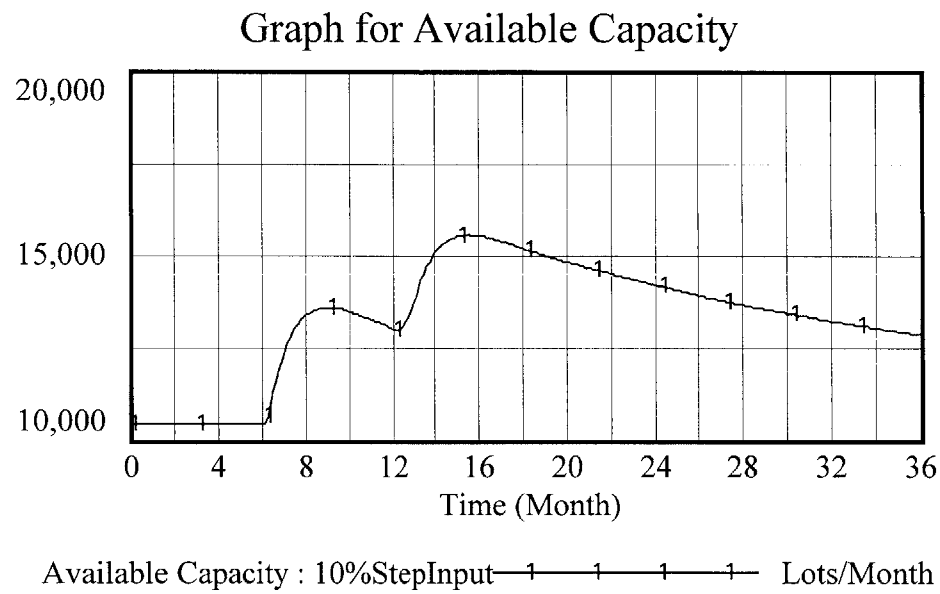

Figure 7.2 Step Response of the Channel Demand for Available Capacity

A number of simulations were performed. One of the observations is that varying time to adjust inventories, including Pre-assembly Inventory Adjust Time (PAT), Time to Adjust Assembly Inventory (TAAI) and Time to Adjust Finished Goods Inventory (TAFGI), has impacts on the oscillatory behaviors of the product inventories. Especially, varying TAAI has a significant impact on the oscillatory behaviors of the production. Shortening TAAI from original 2 weeks to 1 week and to 0.5 week enhances the oscillations in the production inventories including Pre-assembly Inventory, Assembly Inventory and Finished Goods Inventory. Note that the original parameters are PAT = 2 weeks, TAAI = 2 weeks and TAFGI = 2 weeks.

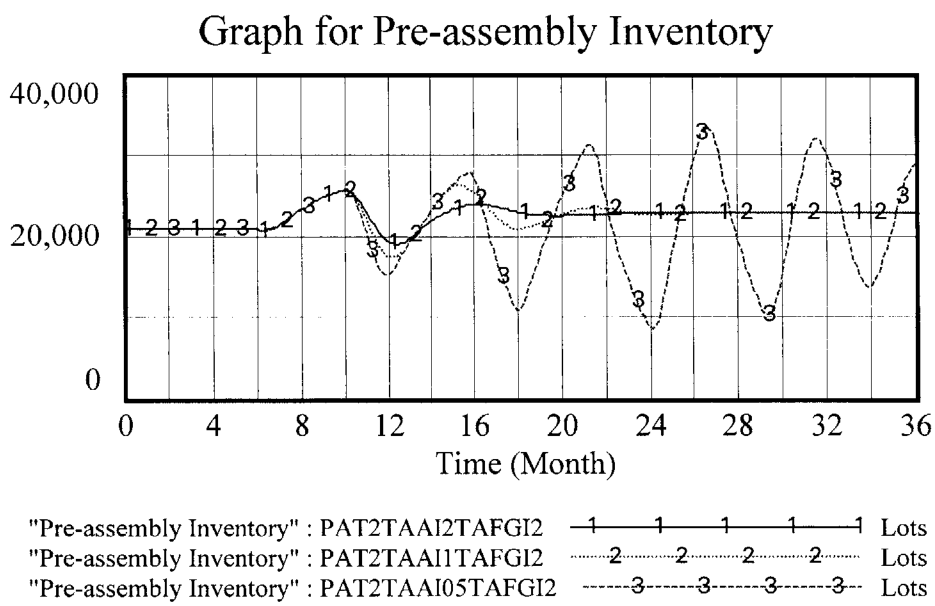

Figure 7.3 Pre-assembly Inventory with Different TAAIs

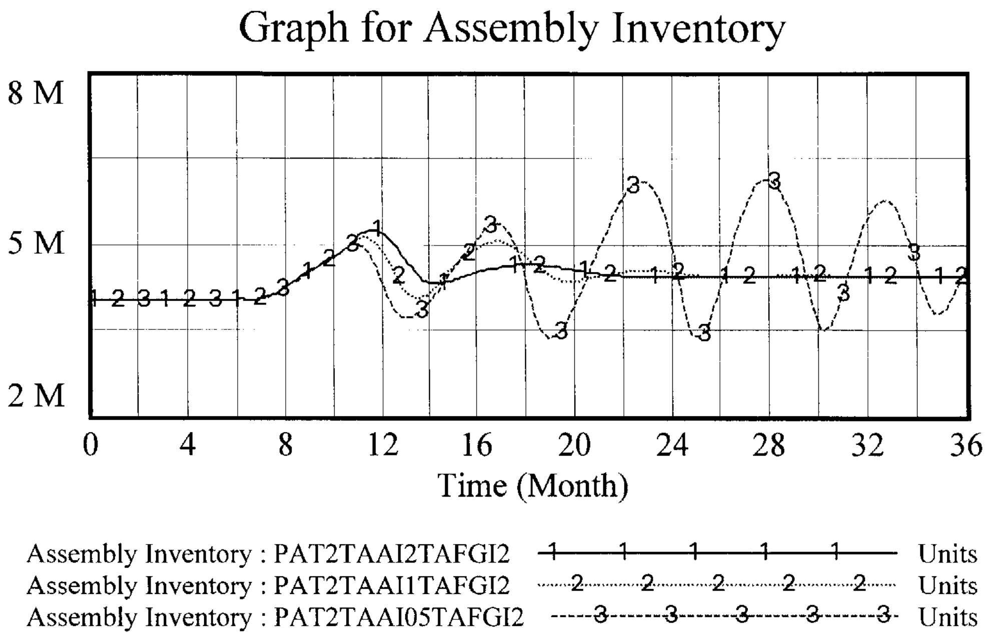

Figure 7.4 Assembly Inventory with Different TAAIs

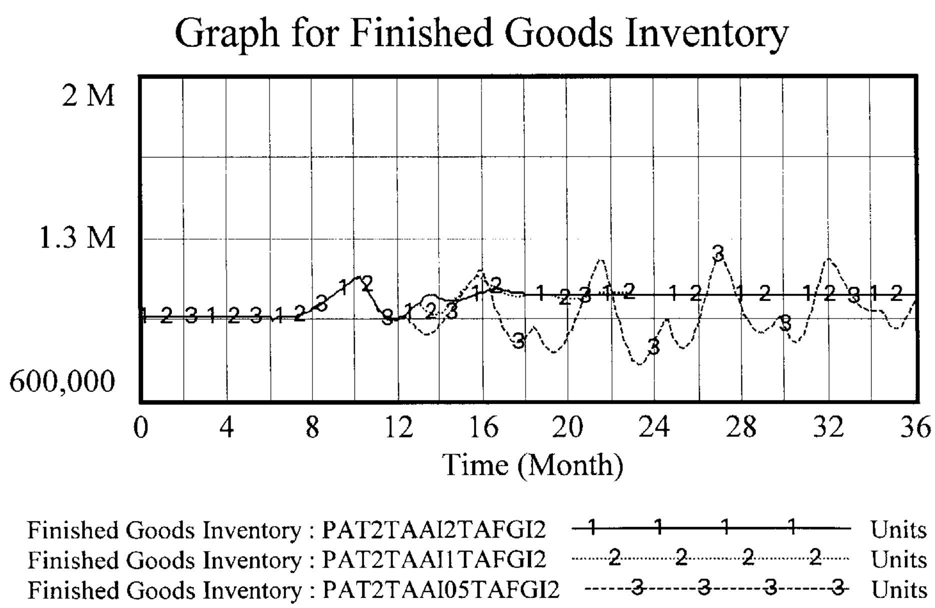

Figure 7.5 Finished Goods Inventory with Different TAAIs

Moreover, by varying these parameters, PAT, TAAI and TAFGI, one surprising insight is that Channel Demand for LSMC Products also oscillates (see Figure 7.6). The oscillation in Channel Demand implies that Channel Demand for LSMC Products is endogenous and is caused by the internal actions e.g. time to adjust inventories in the productions. Before seeing this insight, most senior managers and many participants believed that the oscillatory demand was exogenous and the exogenous inputs caused the oscillatory behavior in product inventories. Section 7.3will discuss more details on relation of the fluctuation of Channel Demand for LSMC Product and how LSMC adjusts its production inventories.

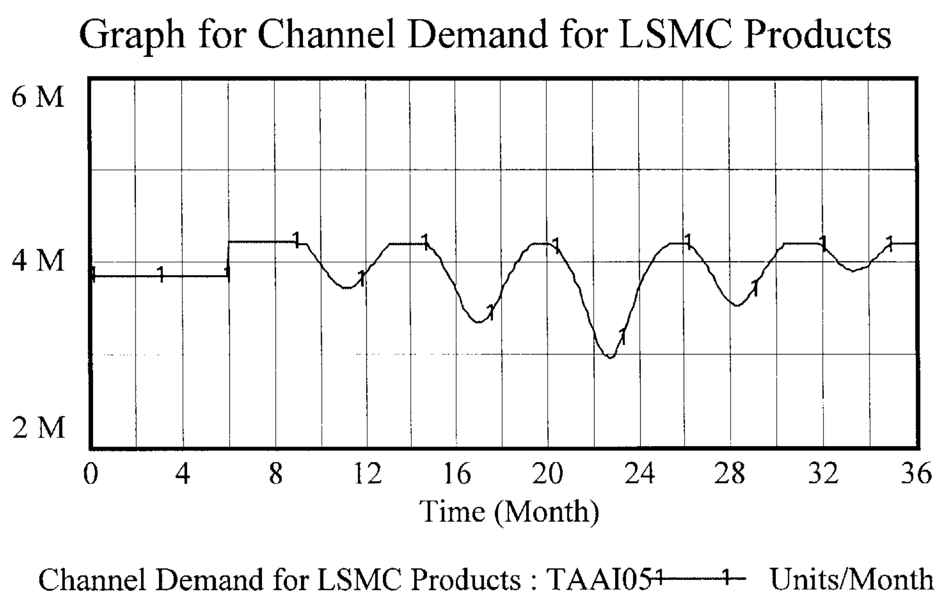

Figure 7.6 Step Response of Channel Demands for LSMC Ships

Next, LSMC model is excited by ramp input and sinusoidal input. These simulations demonstrate how well the production reacts to different types of demand inputs and how robust the model is.

7.2.2 Ramp Response Simulation

After LSMC introduces a new product, the demand soars in the first period. The manufacturing will ramp its production to meet the demand. The production ramp is the time it takes to bring the production starts from low/no capacity to full capacity. In this case, the simulation assumes about one year ramping and 100% a year or 8.33% a month starting from 6th to 18th month. Figure 7.7 illustrates that ramping production also causes oscillations in both the production inventories and Channel Demand for LSMC Products. The oscillations caused by the ramping production are also another insight.

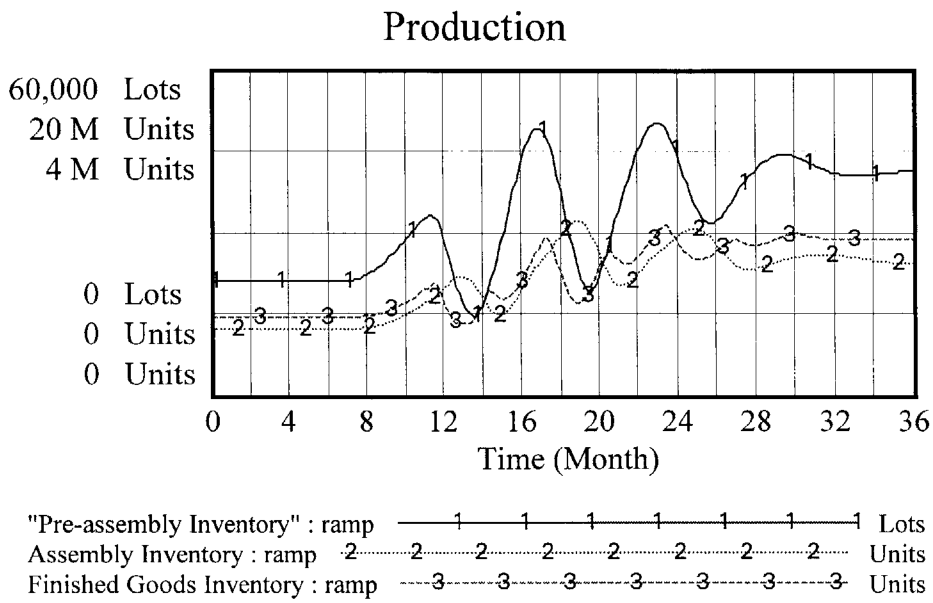

Figure 7.7 Ramp Response of the Channel Demand for Product Inventories

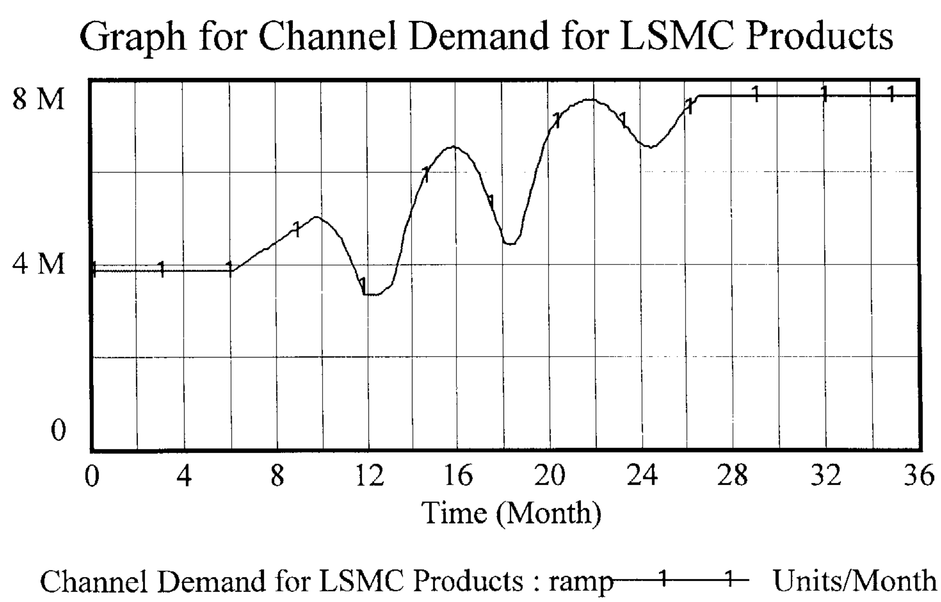

Figure 7.8 Ramp Response of Channel Demands for LSMC Ships

7.2.3 Sinusoidal Response Simulation

LSMC's products are upstream of the PC supply chain. It is possible that downstream of the PC supply chain such as PC makers and PC distributors also generate an oscillatory demand in the PC market. For example, during a holiday season, PC sale is expected to be the highest. A sinusoidal or fluctuation demand with 10% amplitude and 12-month period is applied to this simulation. Undoubtedly, this cyclic behavior of demand also generates the oscillations in the production inventories and Channel Demand LSMC Products.

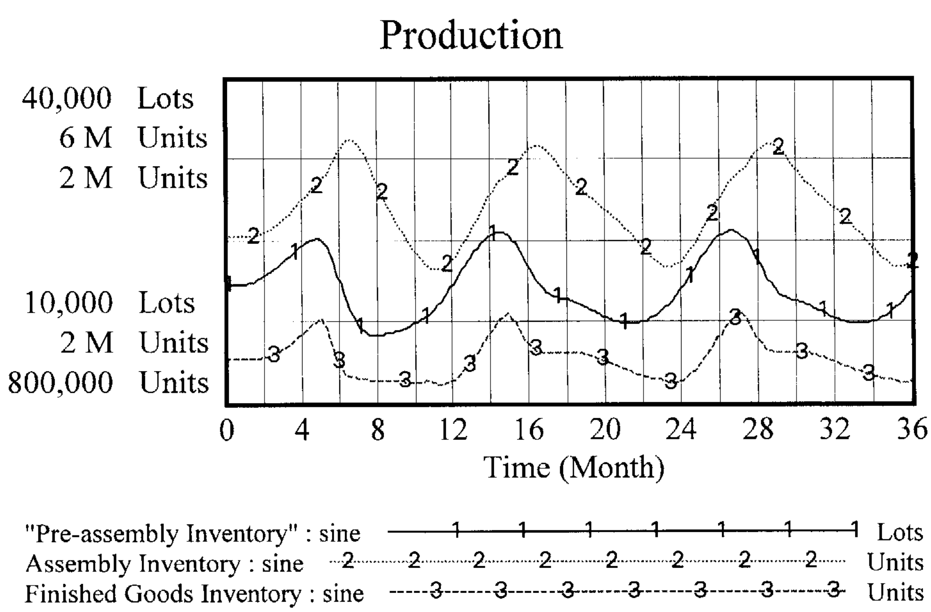

Figure 7.9 Sinusoidal Response of the Channel Demand for Product Inventories

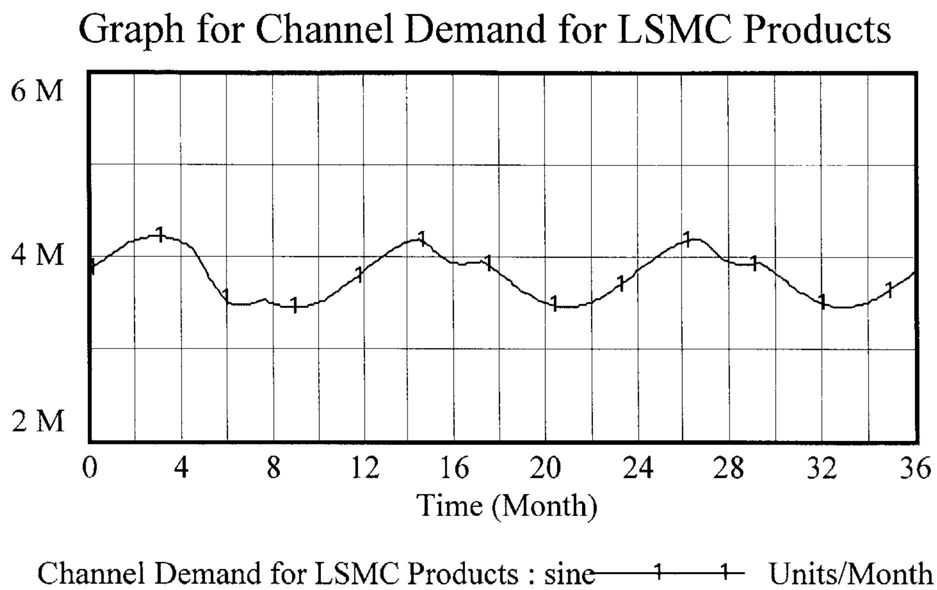

Figure 7.10 Sinusoidal Response of Channel Demands for LSMC Ships

The important insight from the simulations in this section is Channel Demand for LSMC Products is endogenous and the oscillations in Channel Demand are caused by internal actions including 1) varying time to update production inventories such as PAT, TAAI and TAFIG and 2) ramping production. Another result suggests that the model is robust to those inputs, step function, ramp function and sinusoidal function. Robustness of the model could be investigated further with different shapes of inputs. Sinusoidal response, however, does not generate an insight. The step input and the ramp input suffice to excite the dynamics of the model.

7.3 Eigenvalue Analysis

LSMC supply chain model was formulated as a system of nonlinear differential equations. To apply eigenvalue technique, first, the model is linearized at any point in time and then the eigenvalues and eigenvalue elasticity are calculated. Eigenvalue elasticity (see Appendix B) is a change in an eigenvalue relative to a change in a loop or link gain. This measure helps identifying the links or loops that contribute most significantly to the model behavior

For a nonlinear differential equation, a system can be represented as

$$\dot{x} = f(x) \text{ -----(1)}$$

where x is a vector of the stock variables, $f(x)$ is a nonlinear function of x and $\dot{x}$ is a derivative of x. A nonlinear system can be linearized for a small variant about an operating point $\tilde{x}$ (see Appendix B) and equation (1) becomes

$$\dot{\tilde{x}} = A\tilde{x} + B \text{ -----(2).}$$

Equation (2) is a system of linear differential equations where $\tilde{x}$ is a vector of the stock variables, $\dot{\tilde{x}}$ is a derivative of $\tilde{x}$, A is a state transition matrix and B is a constant vector. The eigenvalues of the matrix A determine the modes or behaviors of the system. From LSMC supply chain model in Chapter 6 , the vector $\tilde{x}$ can be represented as

$$\tilde{x} = \begin{bmatrix} \textit{Pre-assembly Inventory} \\ \textit{Expected Chanel Demand for LSMC Product} \\ \textit{Available Capacity} \\ \textit{Finished Goods Inventory} \\ \textit{Channel Order Backlog} \\ \textit{Assembly Inventory} \\ \textit{Historical Demand} \\ \textit{Perceived LSMC Fraction Orders Filled} \\ \textit{Perceived Present Demand} \end{bmatrix} \text{-----(4).}$$

Analyzit (Hines, 1999) is applied to calculate the eigenvalues and eigenvalue elasticities for LSMC supply chain model. Note that Analyzit is a JAVA program developed by Professor Hines, System Dynamics group at MIT. After running Analyzit, there are two additional stock variables, Perceived LSMC Fraction Orders Filled Stock 2 and Perceived LSMC Fraction Orders Filled Stock 3. A Smooth3 function for Perceived LSMC Fraction Orders Filled in Vensim is considered to be three-stock variables, which have three eigenvalues. Therefore,

$$\tilde{x} = \begin{bmatrix} \textit{Pre-assembly Inventory} \\ \textit{Expected Channel Demand for LSMC Product} \\ \textit{Available Capacity} \\ \textit{Finished Goods Inventory} \\ \textit{Channel Order Backlog} \\ \textit{Assembly Inventory} \\ \textit{Historical Demand} \\ \textit{Perceived LSMC Fraction Orders Filled} \\ \textit{Perceived Present Demand} \\ \textit{Perceived LSMC Fraction Orders Filled Stock 2} \\ \textit{Perceived LSMC Fraction Orders Filled Stock 3} \end{bmatrix} \text{-----(5).}$$

To analyze the model, TAAI = 0.5 month was chosen to enhance oscillation. Observe that the growing amplitude of oscillation in Pre-assembly Inventory occurs in the period T of Time between the 10^{th} and 32^{nd} months (see Figure 7.1). The cycles from one peak to another are $T_1 \approx 5.75$ weeks, $T_2 \approx 5.25$ weeks, $T_3 \approx 5.5$ weeks and $T_4 \approx 5$ weeks.

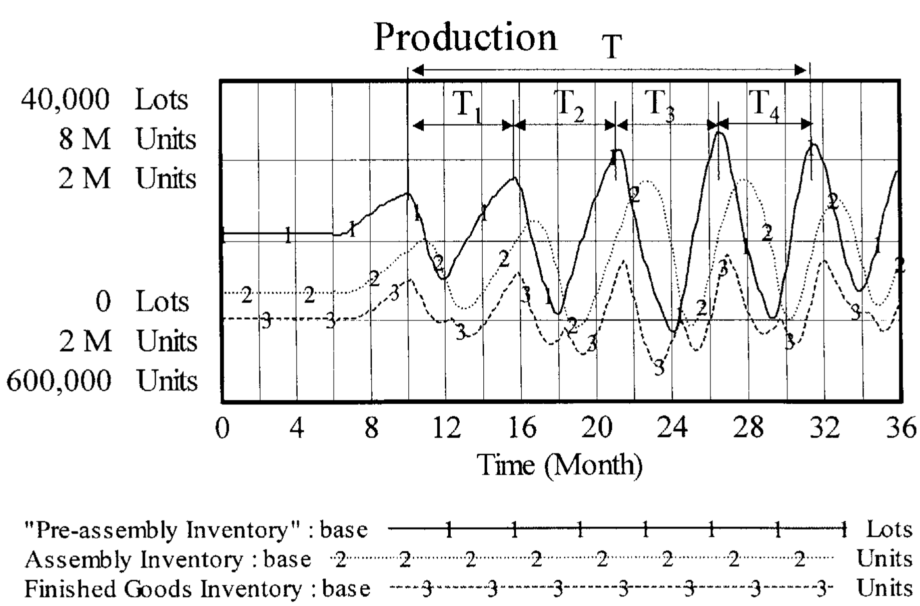

Figure 7.11 Step Response of Production Inventories

The next steps are to identify which eigenvalues in the period T contribute to the oscillations and then to examine which links and loops contribute to the oscillatory behavior in the system by investigating eigenvalue elasticities.

From Analyzit, at t =15.75, the eigenvalues of the system are

$$\lambda_{t=15.75} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ \lambda_{17} \\ \lambda_8 \\ \lambda_9 \\ \lambda_{10} \\ \lambda_{11} \end{bmatrix} = \begin{bmatrix} -0.01667 \\ -3.95215+0.22164j \\ -3.95215-0.22164j \\ -4 \\ \mathbf{-0.03372+1.39447j} \\ \mathbf{-0.03372-1.39447j} \\ \mathbf{-1.44903+1.06347j} \\ \mathbf{-1.44903-1.06347j} \\ -0.18753 \\ -1.94237 \\ -1.00030 \end{bmatrix} \quad \text{-----(6).}$$

Interestingly, two pairs of eigenvalues which have the period of $\frac{2\pi}{1.39447} = 4.5058$ weeks and the period of $\frac{2\pi}{1.06347} = 5.9082$ weeks are close to the periods T_1 and T_2. However, λ_5 and λ_6 have smaller damping factors than λ_7 and λ_8 do (i.e. $|\operatorname{Re}(\lambda_5)| < |\operatorname{Re}(\lambda_7)|$). This implied that the eigenvalues λ_5 and λ_6 account for the amplitude of the oscillations in the production inventories (see Figure 7.11) more than λ_7 and λ_8 do.

From the Analyzit, at time t = 15.75, the eigenvalue elasticities of eigenvalues λ_5 and λ_6 are presented in Table 7.1. Note that the table is sorted by the imaginary part of the eigenvalue elasticities.

Table 7.1 Eigenvalue Link Elasticities for λ_5 and λ_6 at t = 15.75

For λ_5 and $\lambda_6 = -0.3372 \pm 1.39447j$	***Eigenvalue***	***Elasticities***
Link	***Real***	***Imaginary***
Pre-assembly Inventory-->Assembly Inventory	-1.61092	**0.36455**
Assembly Inventory-->Finished Goods Inventory	8.58979	**0.30081**
Finished Goods Inventory-->Channel Order Backlog	10.41305	**0.26731**
Channel Order Backlog-->Pre-assembly Inventory	8.80399	**0.20991**
Finished Goods Inventory-->Finished Goods Inventory	-11.63459	-0.20458
Pre-assembly Inventory-->Pre-assembly Inventory:	-6.76211	-0.14131
Assembly Inventory-->Assembly Inventory	-6.7621	-0.14131
Expected Channel Demand for LSMC Products-->Pre-assembly Inventory:	1.36878	0.0875
...	...	...

The imaginary parts of link elasticities of the eigenvalue measure which links contribute significantly to the oscillatory behavior of the model. From Table 7.1, it can be seen that the links that contribute to the oscillatory behavior of LSMC model at time t = 15.75 are the first four links in Table 7.1. Moreover, those four links form a loop called Loop L1 (see Figure 7.12).

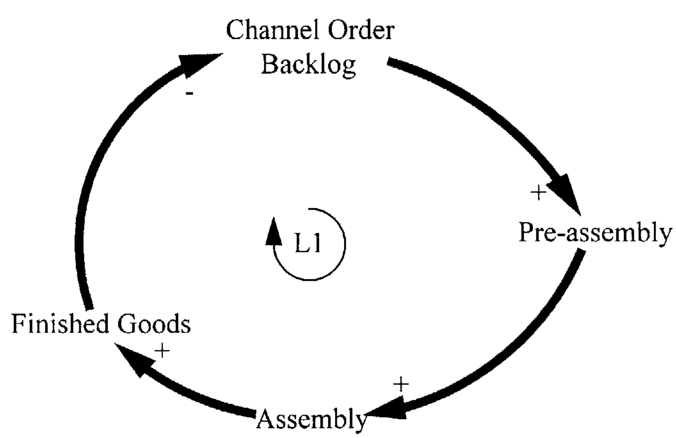

Figure 7.12 Loop L1 formed by the Links in Table 7.1

This result reveals that Loop L1 contributes to the to the oscillatory behavior of LSMC model at time t = 15.75.

To compare the previous result with another time step, the simulation was performed at time t = 21.65. From Analyzit, at t =21.65, the eigenvalues of the system are

$$\lambda_{t=21.25} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ \lambda_6 \\ \lambda_{17} \\ \lambda_8 \\ \lambda_9 \\ \lambda_{10} \\ \lambda_{11} \end{bmatrix} = \begin{bmatrix} -0.01667 \\ -3.95675+0.22609j \\ -3.95675-0.22609j \\ -4 \\ \mathbf{-0.07908+1.39050j} \\ \mathbf{-0.07908-1.39050j} \\ \mathbf{-1.46157+0.97313j} \\ \mathbf{-1.46157-0.97313j} \\ -0.20990 \\ -1.79491 \\ -1.00038 \end{bmatrix} \quad \text{-----(6).}$$

For t = 21.25, two pairs of eigenvalues which have the period of $\frac{2\pi}{1.39050} = 4.5187$ weeks and the period of $\frac{2\pi}{0.97313} = 6.4567$ weeks are close to the period T_2. λ_5 and λ_6 again have smaller damping factors than λ_7 and λ_8 do. From the Analyzit, at time t = 21.25, the eigenvalue elasticities of eigenvalues λ_5 and λ_6 are presented in Table 7.2. Note that the table is sorted by the imaginary part of the eigenvalue elasticities.

Table 7.2 Eigenvalue Link Elasticities for λ_5 and λ_6 at t = 21.75

For λ_5 and $\lambda_6 = -0.07908 \pm 1.39050j$	***Eigenvalue***	***Elasticities***
Link	***Real***	***Imaginary***
Pre-assembly Inventory-->Assembly Inventory	-0.48895	**0.38359**
Assembly Inventory-->Finished Goods Inventory	4.11261	**0.29427**
Finished Goods Inventory-->Channel Order Backlog	4.27212	**0.20801**
Channel Order Backlog-->Pre-assembly Inventory	4.74314	**0.19417**
Finished Goods Inventory-->Finished Goods Inventory	-5.38989	-0.19161
Pre-assembly Inventory-->Pre-assembly Inventory:	-3.20949	-0.14096
Assembly Inventory-->Assembly Inventory	-3.20949	-0.14096
Assembly Inventory→Pre-assembly Inventory	-4.60475	0.08925
...	...	...

Again the first four links in Table 7.2 form Loop L1. Note that at different point in time, t, these four links may not be in this order and may not be the first four links in the table.

7.4 Model Analysis

To explain what cause the oscillation in Loop L1, LSMC supply chain model in Chapter 6 can be simplified as a new causal loop diagram. Figure 7.13 illustrates the new simplified causal loop diagram for LSMC supply chain system.

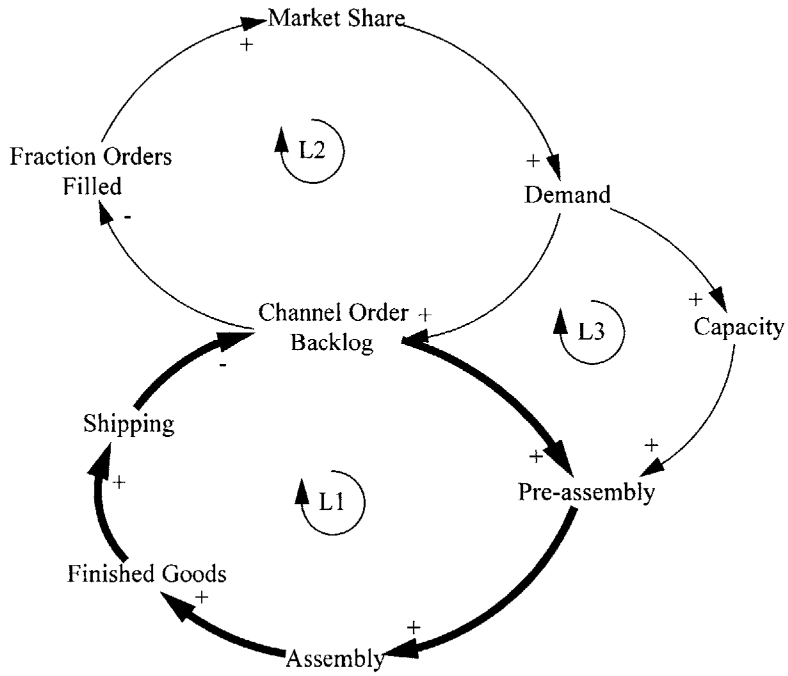

Figure 7.13 LSMC Supply Chain's Simplified Causal Loop Diagram

Because of the delays of Minimum Order Processing Time and Target Delivery Delay (see LSMC Shipping Model in Figure 6.12), when there is an unanticipated 10% of Channel Demand, Shipping still continues at the initial rate and Shipping does not changes it rate immediately. So Channel Order Backlog builds up. When the backlog occurs, LSMC increases its productions. However, when the backlog occurs, the order fulfillment ratio drops as well. Customers choose to buy products from LSMC's competitors instead and that leads to decreasing demand of LSMC products. However, the production department already received a signal to increase the productions and it builds up the inventory. When the inventory exceeds the backlog, LSMC will cut its productions. Without the backlog, the order fulfillment ratio increases to normal level. However, with the decrease in the production, the backlog will occur again. The simulations in Section 7.2 suggest that the oscillation of the production inventories will continue for a period of time before it reaches a steady level. Also, all the eigenvalues in Section 7.3 have negative real parts which suggest that the system will reach a steady state at some point in time. Note that because LSMC supply chain model is a system of nonlinear differential equations, the eigenvalues of a linearized model change overtime and at some point in time the eigenvalues might have positive real parts which could lead to an unstable system. However, the simulations suggest that the system reaches a steady level.

7.5 Supporting Analysis

To support the result that loop L1 indeed causes the oscillation in the supply chain model, loop knockout technique is performed to analyze the oscillation. Loop knockout is one of the traditional techniques in system dynamics to study loop dominance.

First, Loop L1 is disconnected from the system. This can be done by disconnecting the link from Finished Goods to Shipment. Figure 7.14 demonstrates the idea how to disconnect Loop L1 from the system. The simulation in Figure 7.15 illustrates that there is no oscillation in Expected Channel Demand. The result implies that Loop L1 contributes to the oscillations in LSMC supply chain model.

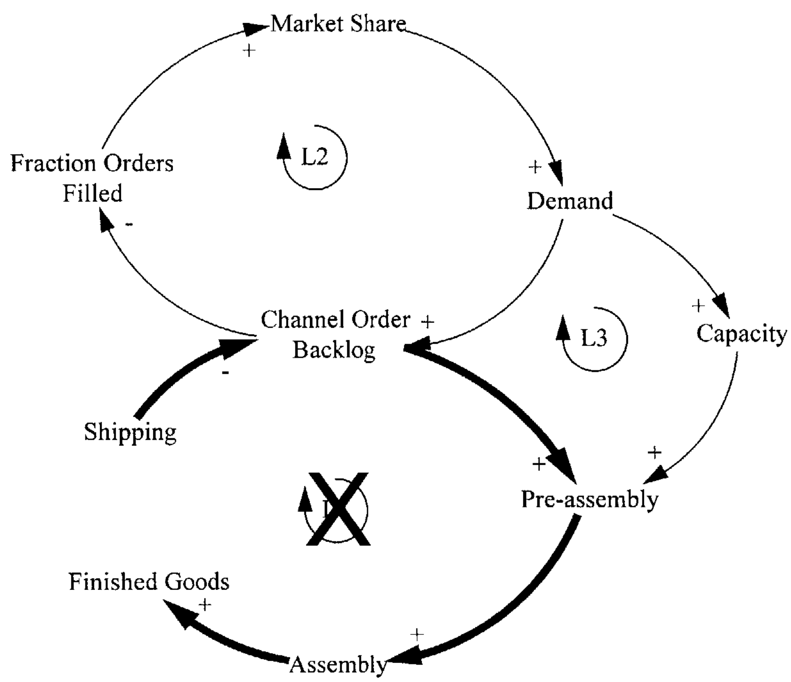

Figure 7.14 Disconnect Link from Finished Goods and Sales in Loop L1

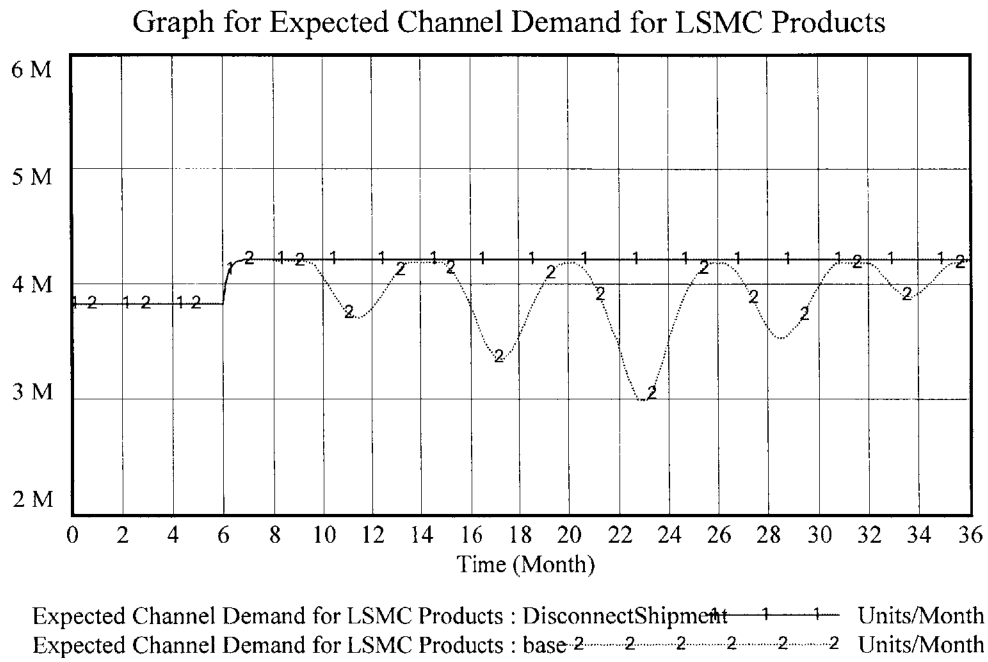

Figure 7.15 Step Responses of Expected Channel Demand When Loop L1 is Broken

Next, the link from Market Share to Demand in loop L2 is disconnected (see Figure 7.16).

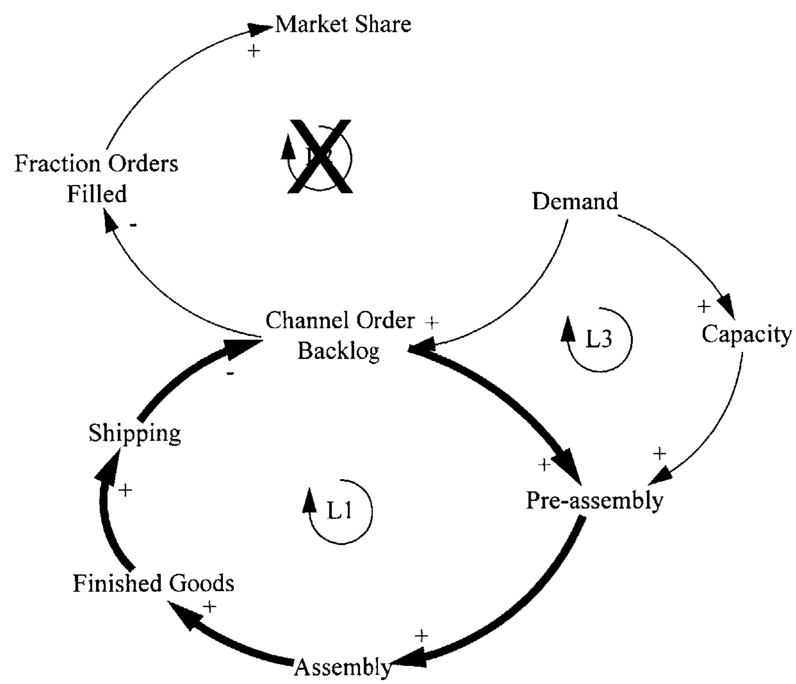

Figure 7.16 Disconnect Link from Finished Goods and Sales in Loop L1

From the simulations, the oscillation still occurs in the production inventories; Pre-assembly Inventory, Assembly Inventory and Finished Goods Inventory. The oscillations continue implying that Loop L2 does not cause the oscillations. Both results from disconnecting Loop L1 and disconnecting Loop L2 imply that Loop L1 indeed contributes to the oscillation that occurs in loop L1 and also to Expected Channel Demand in the complete supply chain model

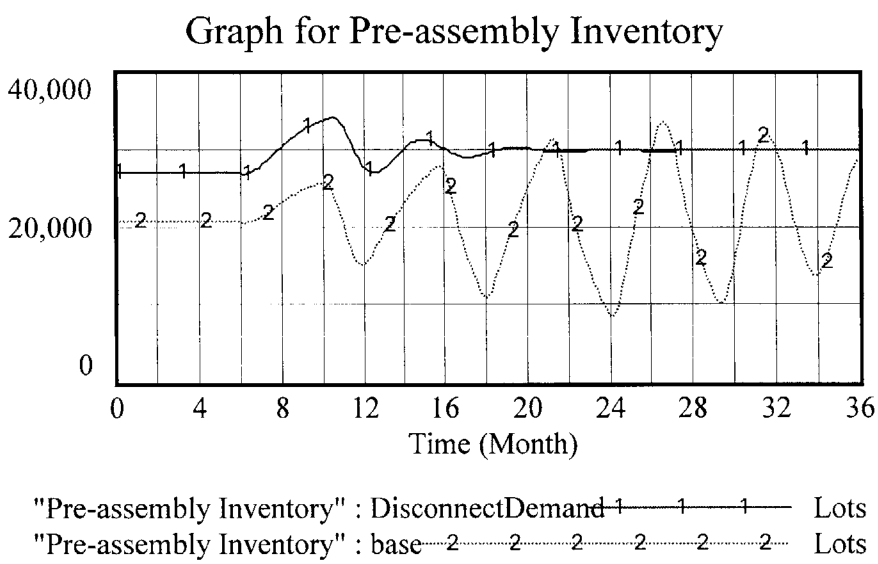

Figure 7.17 Step Responses of Pre-assembly Inventory When Loop L2 is Broken

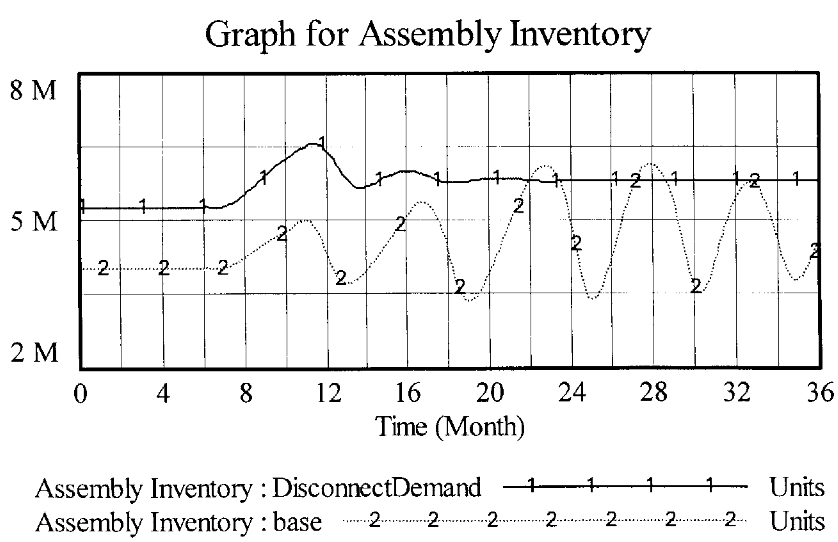

Figure 7.18 Step Responses of Assembly Inventory When Loop L2 is Broken

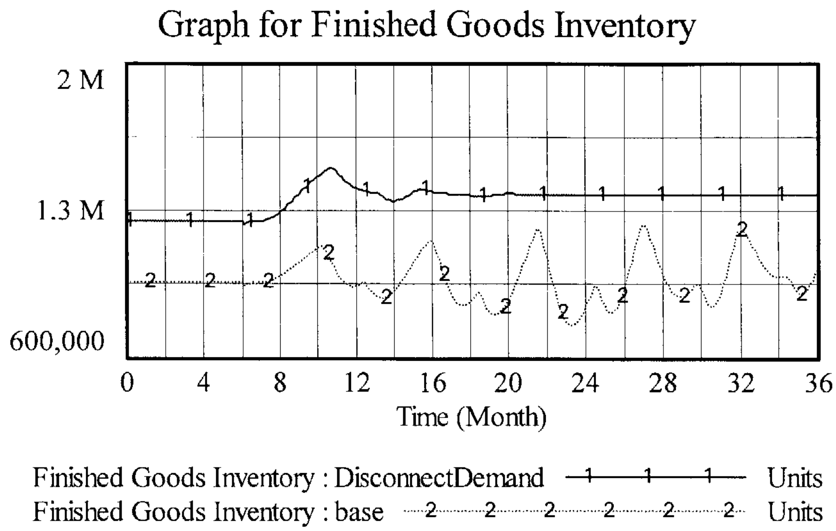

Figure 7.19 Step Responses of Finished Goods Inventory When Loop L2 is Broken

7.6 Suggested Policies

One on LSMC's concerns is the fluctuation in demand. From the analysis in this chapter, Loop L1 in Figure 7.13 is the loop that causing the oscillations in LSMC supply chain model. Policies for lessening or stopping the oscillations should involve in Loop L1. One policy that could be easy to implement is build up a safety stock to reduce a backlog. One experiment is to build up a 1-week or 0.25 month for Safety Stock Coverage. To see the differences, TAAI is chosen at 0.5 month. From the simulation, it can be seen that the production inventories are less oscillatory and they reach the steady states in a short period.

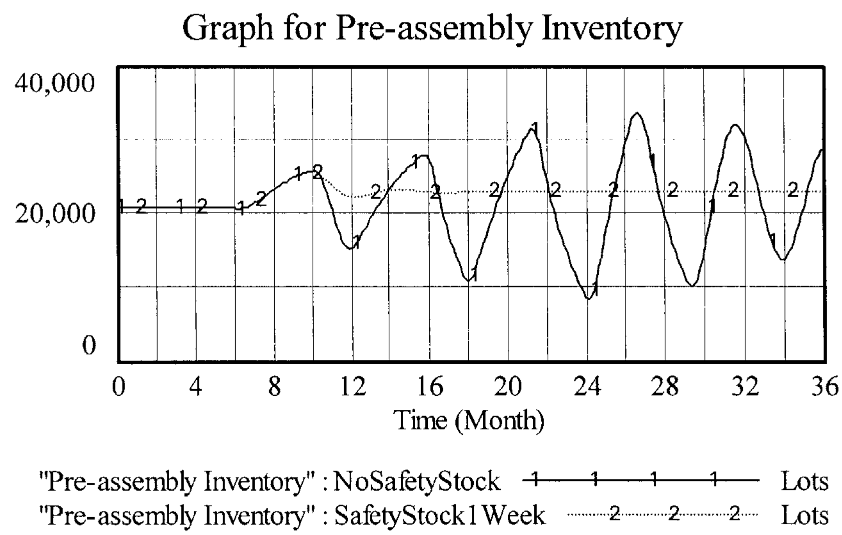

Figure 7.20 Step Responses of Pre-assembly Inventory with and without Safety Stock

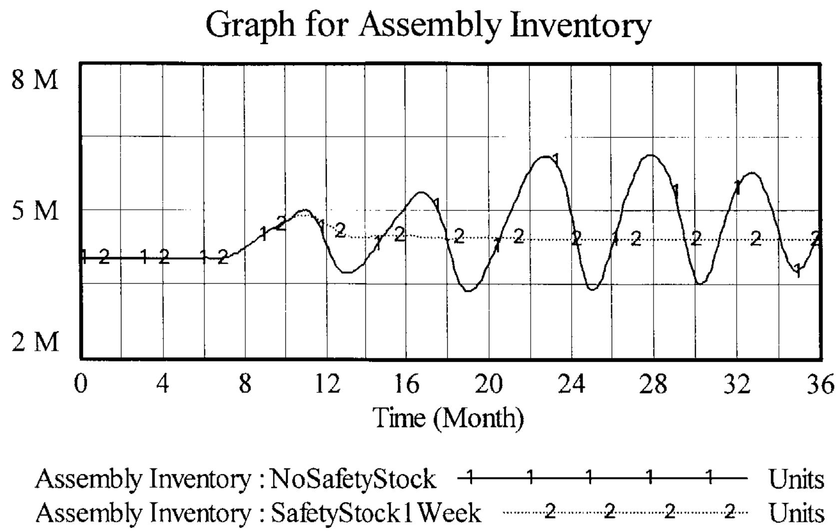

Figure 7.21 Step Responses of Assembly Inventory with and without Safety Stock

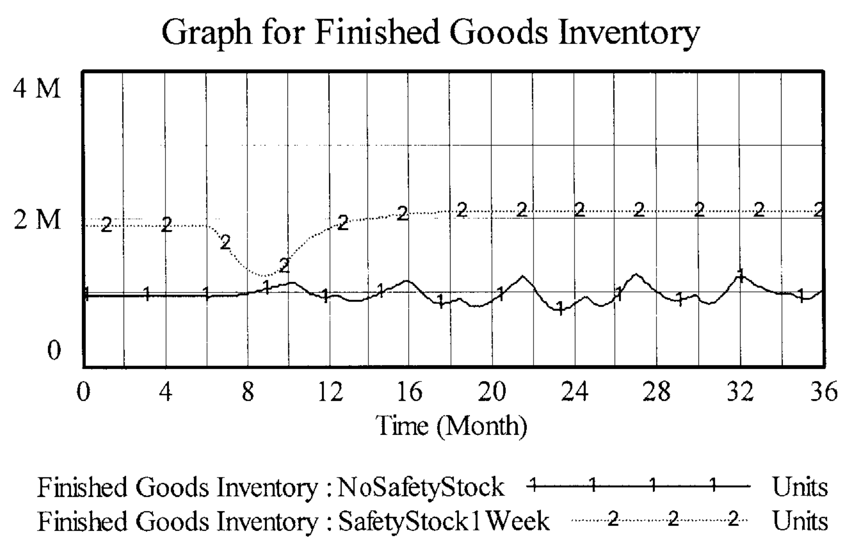

Figure 7.22 Step Responses of Finished Goods Inventory with and without Safety Stock

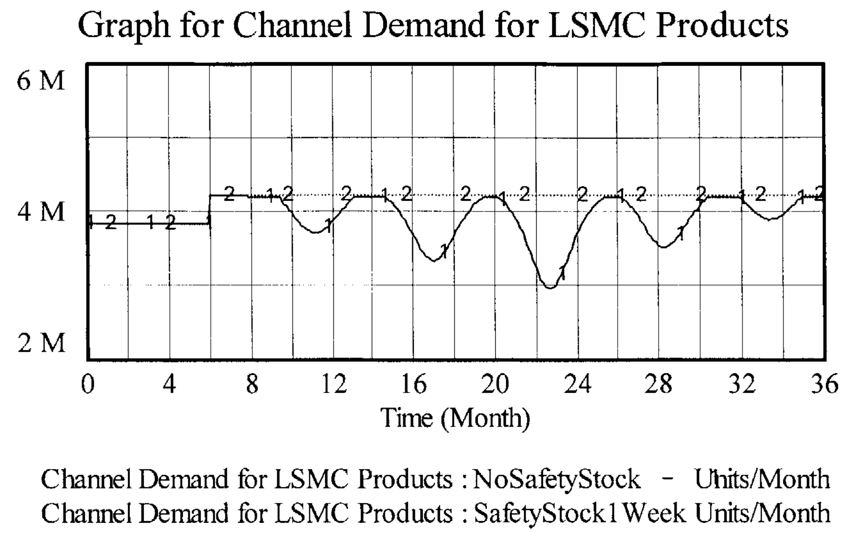

Figure 7.23 Step Responses of LSMC Channel Demand with and without Safety Stock

7.7 Conclusions

The simulations and analyses in this chapter demonstrate that the demand is endogenous and the oscillations in Channel Demand are caused by internal actions including 1) varying time to update production inventories such as PAT, TAAI and TAFIG and 2) ramping production. Before the results from the simulations and the analyses, most participants had the impression that the oscillation in the demand was purely exogenous and caused by the fluctuation in the market. Eigenvalue techniques and loop knockout are useful tools to identify the cause of LSMC supply chain model's oscillatory behaviors and also to design a policy to lessen or stop the oscillatory behaviors.

However, LSMC supply chain model in this study is not an actual LSMC supply chain in the real world. The results from this study suggest that the oscillations in the production inventories could happen if the real LSMC supply chain model has a similar structure. The results also suggest that safety stock may help solve the oscillations behavior in the product inventories and in the capacity.

Chapter 8 Summary

This chapter summarizes the learning experiences of the system dynamics process that was used throughout this study. Several ideas for future research are also presented. The insights and results of the system dynamics process are also included in this chapter.

8.1 Conclusion

The objective of this thesis was to apply the system dynamics approach to LSMC's supply chain problem. The author want to emphasize that LSMC supply chain model in this thesis is not the real world LSMC supply chain model. The causal loop diagram and the model were created based upon information and mental models provided by a team of senior mangers and other participants who were familiar with the supply chain issues at LSMC. The models represent a simplified version of the real world and should not be expected to provide exact predictions. However, the analyses and the results from this these may help explain the problem statements which are defined as follows:

1. The fluctuation in the finished goods (FG) inventory oscillates and the amplitude is large compared to demand and capacity.

2. LSMC's capacity relative to desired capacity oscillates and the amplitude is growing.

From the analysis, the major conclusions are:

1. The participants are more concerned about production and capacity than other operations and facilities. When the oscillation or other problems occurs, the participants from manufacturing tend to counter the problem by issuing more policies related to production. This conclusion was drawn from the causal loop diagram/momentum policies mapping in Section 5.19.

2. The oscillatory behavior in demand is endogenous. One of the reasons that causes the oscillation in the production inventories, LSMC's demand and capacity is internal actions including 1) varying time to update production inventories such as PAT, TAAI and TAFIG and 2) ramping production.

3. A policy such as building up a safety stock may reduce or stop the oscillation in the production inventories, LSMC's demand and capacity

This thesis has demonstrated that the standard system dynamics process can be applied to developing an understanding of the supply chain problem at LSMC. Moreover eigenvalue analysis and loop knock out are useful tools to identify cause of the oscillations in LSMC supply chain model.

8.2 Reflections

Many managers and business planners generally do not realize the impact of feedback lops in systems and they even seem skeptical about system thinking and system dynamics. To motivate these people in the business world to participate in the system dynamics process and to convince them of the value of system thinking and system dynamics are somewhat challenging. Furthermore, system dynamics is a long process and it often takes much effort to generate a story, to create a model and to analyze the model.

The project with LSMC started very slowly and there was doubt about the benefit of using system dynamics as a tool. However, the contact person at LSMC, had a significant impact on the project by coordinating and assembling those senior managers for the interviews and helping smooth the process of this research.

Development of the causal loop diagram and momentum policies allows the participants to share learning experiences and also see the problems, e.g. oscillatory behavior in inventories, demand and capacity, from different angles. Especially the lessons and the results of the system dynamics in Chapters 5, 6 and 7 demonstrate that system dynamics is a powerful tool to learn about insights of the problems and to reemphasize the feedback loop concept to many people. The results from the simulations and analyses allow the participants to see the problem is endogenous, not exogenous, and policy makers will be able to use these insights to design better policies to deal with their problems. Although the model does not need to be calibrated to historical data, the results and insights from the simulations and the analysis are important and often enough to allow managers to understand the cause of the problem.

Based upon its results, the people who were involved in the project have had very positive responses. The prospect of future work looks very promising. The key people will continue to support the project and are eager to learn more insights from it.

8.3 Ideas of Potential Future Work

The future research listed below could lead to more effective way to solve the oscillation problems in LSMC's production inventories, demand and capacity.

1. Expanding the causal loop diagrams to increase the understanding of the problem. It would be interesting if the problem was approached from different areas (see Figure 5.20) such as R&D and OEM.

2. Expanding or even restructuring the model and studying the impact of:

a. Product mix and split bin. With many varieties of LSMC products, the sequencing of what products are to be produced and which machines to produce in the process may have an interesting dynamic impact on LSMC's demand and capacity. Some of the products may take longer and require more steps. Furthermore, some steps may need to be produced in large volume.

b. Market segmentations and pricing strategy. Segmenting products to low-end market and high-end market makes the model more realistic and captures some of the missing dynamics. Likewise, including prices of LSMC's and competitors' products makes the system more realistic.

c. Customer order change. There are four types of customer changes: 1) Type of products, 2) Quantity of products, 3) Schedule of delivery and 4) Place for delivery. It would be very interesting to see which type of change may or may not have impact on the overall dynamic behaviors.

d. Competitors' market share and products. Competitors' market share and products may be added to the model to see how they might impact the overall behavior.

e. Suppliers' and OEMs' supply chains. The model can be extended by including suppliers' and OEM's supply chains. The extended network will be a challenging work, and the studies may benefit the whole supply chain stream.

f. Other products. The study can be expanded to include other LSMC's products, e.g. network and wireless communication equipment, and services.

g. Outsourcing. Because of high cost and long delay of building a production facility, outsourcing may be able to stabilize and reduce the backlog.

h. Web-based supply chain management. This would be a significant change in the parameters and even the structure of the model. Electronic communication with OEMs and other retail partners gives LSMC more accurate and timely information on buying trends. The electronics and web-based transactions allow LSMC to communicate better with suppliers and make outsourcing a more viable option.

3. Use Analyzit to analyze other part of the model to find more insights.
4. Design policies to counter the problem and use the tools to help gain insight into the new system with added policy structure.
5. Extend system dynamics to other areas beyond supply chain application.

Appendix A List of Variables

These are the variables that the participants generated during the first meeting.

Ability to set equipment lead-time (3 years)
Acceptable path
Asset turns
Availability of raw material
Backlog
Capacity
Capital e.g. servers
Change order
Complexities of international regulation
Cost
Customer specification
Cycle time
Degree of specification of process
Demand
Demand availability
Designing product life cycle
Excess demand
Fathom demand
Forecast accuracy
Interchangeability factor, resource
Inventory – Unit
Inventory - Value
Inventory obsolescence
Inventory shrinkage
Inventory value
Location of the factories
Machine downtime
Market segment share
Material acquisition cost
Mean time to repair
Number of components in a product
Number of days in inventory
Number of employee
Number of factories
Number of path of supply chain
Number of planner
Number of product transition
Number of products
Number of steps in process
Number of subcontracts
Number of suppliers
Number of transition
Order fulfillment lead-time
Overhead cost
Percentage of customizations
Percentage of defective source material
Percentage of delivery performance
Percentage of order fill on time
Percentage of outsource vary each step
Percentage of product mix
Planning time
Point in the life cycle of the product
Price
Process sequencing/order
Product cancellation
Product lifetime
Product maturity
Production growth rate
Profit margin
Safety stock
Similarity of factories
Similarity of processes
Spare cost
Supplier capacity investment (indirect) e.g. memory shortage
Supplier lead-time
Supplier ramp speed
Supply line
Target capacity
Target utilization
Tech licensing
Time of customer to change order
Time to certify
Time to change data
Time to product transition
Time to ramp product
Total source lead-time
Transparency of information
Utilization
Warranty cost
Yield

Appendix B Mathematical Representation

B.1 System Representation

A system dynamics model with level variables $x(t) = [x_1(t) \quad x_2(t) \cdots x_n(t)]'$ and non-level (rates and auxiliaries) variables $y(t) = [y_1(t) \quad y_2(t) \cdots y_m(t)]'$ can be represented in the form of nonlinear differential equations:

$$\begin{aligned} \dot{x}(t) &= f(x(t), y(t), t) \\ y(t) &= g(x(t), y(t), t) \end{aligned} \text{-----(1)}$$

where t denotes time and $t \geq 0$. Note that the symbol, $'$, denotes a transpose of matrix.

For an autonomous or a time invariant system, i.e. independent of t, the system (1) can be reduced to:

$$\begin{aligned} \dot{x}(t) &= f(x(t), y(t)) \\ y(t) &= g(x(t), y(t)) \end{aligned} \text{------(2)}$$

For convenience, the subscription t is omitted. Hence the equation (2) becomes

$$\begin{aligned} \dot{x} &= f(x, y) \\ y &= g(x, y) \end{aligned} \text{-----(3)}$$

Many properties of linear systems do not hold for nonlinear systems. For example, the principal of superposition, one of the most fundamental properties of linear systems, is not valid for nonlinear systems. Nonlinear systems in general are not well behaved and often exhibit very wild and unusual behavior. Furthermore, for nonlinear systems, it is not possible to derive closed-form solutions of differential equations. Therefore, in general, the approximation, numerical solution and simulation are the methods for analyzing nonlinear systems.

B.2 Linearization of Nonlinear Systems

A nonlinear system can be linearized for small variants about an operating point, $(x, y) = (\tilde{x}, \tilde{y})$ by expanding it into Taylor's series and ignoring second and higher order terms. Hence, the linearized system of (3) becomes

$$\dot{\tilde{x}} = A\tilde{x} + B\tilde{y} + b \text{ -----(4)}$$
$$y = C\tilde{x} + D\tilde{y}$$

Equation (4) can be expressed in reduced form,

$$\dot{\tilde{x}} = J\tilde{x} + b \text{ -----(5)}$$

where

$$J = A + B(I - D)^{-1}C \text{ -----(6)}$$

The matrix $J = \dfrac{\partial \dot{x}_i}{\partial x_j}$ is known as the Jacobian matrix.

B.3 Eigenvalue

Consider a linear differential equation:

$$\dot{x} = Ax \text{ -----(7)}$$

For an $n \times n$ matrix A, if there exists a nonzero vector v and a scalar λ such that

$$Av = \lambda v \text{ -----(8)}$$

$$(\lambda I - A)v = 0 \text{ -----(9)}$$

then the values of $\lambda = \lambda_i$, for which equation (9) is satisfied are called the eigenvalues corresponding to matrix A. The vector v satisfying equation (9) is called the eigenvector of A associated with eigenvalue λ_i. The set of equation (9) has a solution if and only if

$$|\lambda I - A| = 0 \text{ -----(10),}$$

where $|\bullet|$ is a determinant of matrix. The determinant of matrix A may be expressed in polynomial form as

$$q(\lambda) = \lambda^n + a_1\lambda^{n-1} + a_2\lambda^{n-2} + \ldots + a_n = 0 \text{ -----(11)}$$

Equation (11) is called the characteristics equation corresponding to matrix A. Furthermore, the roots of $q(\lambda)$ are the eigenvalues of matrix A.

The behaviors of a linear dynamic system are determined by the eigenvalues of the matrix A. The real part of the eigenvalue determines the system stability. The positive real part indicates exponential growth and the negative real part indicates decay or goal seeking mode. The imaginary part of the eigenvalue determines the frequency of oscillation. Note that complex eigenvalues always come in a pair of conjugates. Figure B.1 explains the modes of behavior depending on the position of the eigenvalue on the complex plane.

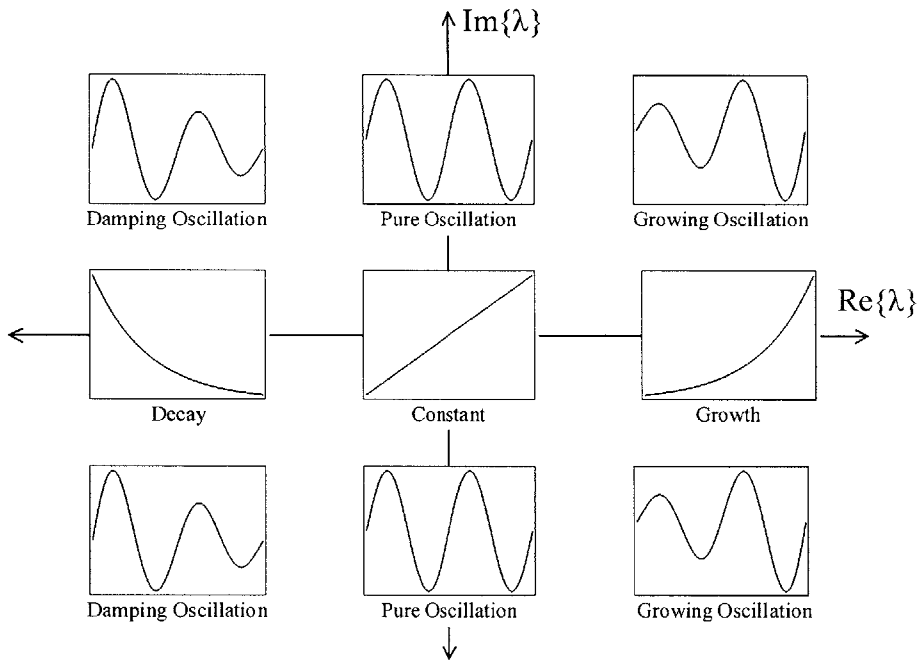

Figure B.8.1 Eigenvalues in Complex Plane and Corresponding Behaviors of a System

Using eigenvalue analysis has some disadvantages:

- The eigenvalue analysis is technique for linear systems only.
- The eigenvalue analysis is an abstract concept and it is, often, not practical and difficult to understand the actual meaning of a system by only examining eigenvalues of the system.

B.4 Eigenvalue Elasticities

Elasticity is the concept that economists use to measure the responsiveness of one variable to a change in another variable. In terms of engineering, the concept of elasticity is one way to analyze sensitivity of a linear time-invariant system. The elasticity or normalized sensitivity is defined as

$$\varepsilon = \frac{\partial \lambda}{\partial k}\frac{k}{\lambda} = \frac{\frac{\partial \lambda}{\lambda}}{\frac{\partial k}{k}} = \frac{\partial(\ln \lambda)}{\partial(\ln k)} \text{------}(12)$$

i.e. the ratio of the fraction change in some function of λ to the fraction change in the parameter k and, theoretically, those changes are very small.

For system dynamics, the traditional way of identifying dominance of feedback loops is to disconnect weaker loops and show that the isolated loops generate behavior similar to that of the whole model. This method is time-consuming and sometime causes confusion. Instead we apply the elasticity concept to identify the dominant feedback loop by measuring for significance of eigenvalue elasticity, i.e. the relative change in a specific eigenvalue from a relative change in a specific loop gain. The eigenvalue elasticity, ε in equation (13), would allow one to understand how the strength of a loop could impact specific modes of behavior. A large elasticity would indicate that the loop is likely to be responsible for generating the behavior mode associated with the eigenvalue.

$$\varepsilon = \frac{\partial \lambda}{\partial g}\frac{g}{\lambda} = \frac{\frac{\partial \lambda}{\lambda}}{\frac{\partial g}{g}} \text{------}(13),$$

where λ is the eigenvalue and g is the loop gain.

The eigenvalue elasticity is dimensionless and is a complex number showing the percentage change in natural frequency and damping of each eigenvalue resulting from one percent change in loop gain. The magnitude of elasticity measures the overall importance of a loop to a mode of behavior. The magnitudes can be used to rank loops by relative dominance over each mode, or to rank modes by relative importance of each loop.

Appendix C Model Documentation

This appendix contains the equations of the model that are used in Chapter 6. Each equation describes the relationship of the variables, the unit of the variable being calculated and a description of the variable.

```
********************************************************
        .Supply Chain Model V 1.0
********************************************************~

Channel Demand=
        Initial Channel Demand * Input
        ~       Units/Month

Input=
        1+STEP(Step Height,Step Time)
        ~       Dimensionless

Indicated Capacity=
        Lot Forecast Demand/Anticipated Total Yield
        ~       Lots/Month

Anticipated Total Yield=
        Line Yield*Component Per Lot Yield*Unit to Component Yield
        ~       Fraction

Capacity Adjustment=
        (Indicated Capacity-Available Capacity)/Capacity Acquisition Delay
        ~       Lots/(Month*Month)

Capacity Replacing=
        Capacity Obsolescence
        ~       Lots/(Month*Month)

Lot Forecast Demand=
        Unit Forecast Demand/Component Per Lot
        ~       Lots/Month
        ~               |

Capacity Acquisition=
        Max(0,Capacity Adjustment +Capacity Replacing)
        ~       Lots/(Month*Month)

Available Capacity= INTEG (
        Capacity Acquisition-Capacity Obsolescence,
                Desired Production Start Rate)
        ~       Lots/Month

Production Start Rate=
        Max(0,MIN(Available Capacity,Desired Production Start Rate))
        ~       Lots/Month
```

Net Production Rate=
Max Gross Production Rate * Line Yield
~ Lots/Month

Shipment Ratio=
Maximum Shipment Rate/Desired Shipment Rate
~ Dimensionless
~ |

Capacity Obsolescence=
Available Capacity/Average Life of Capacity
~ Lots/(Month*Month)

Channel Order Backlog= INTEG (
+Channel Demand for LSMC Products-Order Fulfillment Rate,
Acceptable Backlog)
~ Units

Expected Channel Demand for LSMC Products=
SMOOTH(Channel Demand for LSMC Products,Time to Update Channel Orders)
~ Units/Month

Initial Channel Demand=
5e+006
~ Units/Month

Step Height=
0.5
~ Dimensionless

Step Time=
6
~ Month

Table for Order Fulfillment(
[(0,0)-(2,1)],(0,0),(1,1),(2,1))
~ Dmnl

Sales to Channel=
Desired Shipment Rate*Order Fulfillment Ratio
~ Units/Month

Desired Finished Goods Inventory Coverage=
Minimum Order Processing Time + Safety Stock Coverage
~ Month

Safety Stock Coverage=
0
~ Month

Minimum Order Processing Time=
0.25
~ Months

Maximum Shipment Rate=

Finished Goods Inventory/Minimum Order Processing Time
~ Units/Month

Order Fulfillment Ratio=
Table for Order Fulfillment(Maximum Shipment Rate/Desired Shipment Rate)
~ Dmnl

Gross Assembly Completion=
MIN(Desired Gross Assembly Completion, Maximum Gross Assembly Completion)
~ Units/Month

Net Assembly Completion=
Gross Assembly Completion * Unit to Component Yield
~ Units/Month

Inventory Coverage=
Finished Goods Inventory/Sales to Channel
~ Months

Maximum Gross Assembly Completion=
Assembly Inventory/Time to Complete Assembly
~ Units/Month

Max Gross Production Rate=
"Pre-assembly Inventory"/Manufacturing Cycle Time
~ Lots/Month

"Desired Pre-assembly Inventory"=
Desired Gross Production Rate * Manufacturing Cycle Time
~ Lots

Desired Gross Production Rate=
Desired Net Production Rate / Line Yield
~ Lots/Month

Desired Gross Assembly Completion=
Desired Net Assembly Completion / Unit to Component Yield
~ Units/Month

Desired Assembly Starts=
Max(0, Assembly Inventory Adjustment + Desired Gross Assembly Completion)
~ Units/Month

Desired Net Assembly Completion=
Max(0, Expected Channel Demand for LSMC Products + Finished Goods Inventory Adjustment\
+ Backlog Adjustment * Backlog Switch)
~ Units/Month

Desired Assembly Inventory=
Desired Gross Assembly Completion * Time to Complete Assembly
~ Units

Channel Demand for LSMC Products=
Channel Demand *LSMC Market Share
~ Units/Month

Desired Capacity=
Available Capacity-Channel Demand for LSMC Products/Component Per Lot
~ Lots/Month

Change in Perceived Present Demand=
(Channel Demand for LSMC Products - Perceived Present Demand)/Time to Perceive Present Demand
~ Units/(Month*Month)

Historical Demand= INTEG (
Change in Historical Demand,
Perceived Present Demand)
~ Units/Month

Perceived Present Demand= INTEG (
Change in Perceived Present Demand,
Channel Demand for LSMC Products)
~ Units/Month

Unit Forecast Demand=
Perceived Present Demand * (1+ Indicated Trend*(Time to Perceive Present Demand+Forecast Horizon\
))
~ Units/Month

Indicated Trend=
(Perceived Present Demand -Historical Demand)/(Historical Demand*Time Horizon for Historical Demand\
)
~ 1/Month

Forecast Horizon=
60
~ Month

Change in Historical Demand=
(Perceived Present Demand - Historical Demand)/Time Horizon for Historical Demand
~ Units/(Month*Month)

Time to Perceive Present Demand=
0.25
~ Month

Time Horizon for Historical Demand=
1
~ Month

Acceptable Backlog=
Channel Demand for LSMC Products * Target Delivery Delay
~ Units

Time to Adjust Backlog=
1
~ Month

Backlog Adjustment=

(Channel Order Backlog - Acceptable Backlog) / Time to Adjust Backlog
~ Units/Month

Assembly Start Rate=
Net Production Rate * Component Per Lot * Component Per Lot Yield
~ Units/Month

Backlog Switch=
1
~ Dmnl

Desired Production Start Rate=
Desired Net Production Rate + "Pre-assembly Inventory Adjustment"
~ Lots/Month

Capacity Acquisition Delay=
18
~ Month

Average Life of Capacity=
60
~ Month

Desired Shipment Rate=
Channel Order Backlog/Target Delivery Delay
~ Units/Month

Target Delivery Delay=
0.25
~ Month

Order Fulfillment Rate=
Sales to Channel
~ Units/Month

Assembly Inventory= INTEG (
+ Assembly Start Rate - Net Assembly Completion - Assembly Rejects,
Initial Assembly Inventory)
~ Units

Assembly Rejects=
Gross Assembly Completion - Net Assembly Completion
~ Units/Month

"Pre-assembly Inventory"= INTEG (
+Production Start Rate-Net Production Rate-Production Rejects,
"Initial Pre-assembly Inventory")
~ Lots

Line Yield=
1
~ Fraction

Production Rejects=
Max Gross Production Rate - Net Production Rate
~ Lots/Month

Component Per Lot Yield=
0.97
~ Fraction

Desired Net Production Rate=
Desired Assembly Starts / (Component Per Lot * Component Per Lot Yield)
~ Lots/Month

Component Per Lot=
400
~ Units/Lot

Unit to Component Yield=
0.95
~ Fraction

Assembly Inventory Adjustment=
(Desired Assembly Inventory-Assembly Inventory)/Time to Adjust Assembly Inventory
~ Units/Month

Finished Goods Inventory= INTEG (
Net Assembly Completion-Sales to Channel,
Desired Finished Goods Inventory)
~ Units

Time to Adjust Assembly Inventory=
0.5
~ Month

Initial Assembly Inventory= INITIAL(
Desired Assembly Inventory)
~ Units

"Initial Pre-assembly Inventory"= INITIAL(
"Desired Pre-assembly Inventory")
~ Lots

Time to Complete Assembly=
1
~ Month

Initial Fraction Order Filled=
1
~ Dmnl

Perceived LSMC Fraction Orders Filled=
SMOOTH3I(Order Fulfillment Ratio,Time to Perceive Fraction Orders Filled,Initial Fraction Order Filled\
)
~ Dmnl

Finished Goods Inventory Adjustment=
(Desired Finished Goods Inventory-Finished Goods Inventory)/Time to Adjust Finished Goods Inventory
~ Units/Month

"Pre-assembly Adjustment Time"=
8
~ Month

Desired Finished Goods Inventory=
Desired Finished Goods Inventory Coverage*Expected Channel Demand for LSMC Products
~ Units

Manufacturing Cycle Time=
2
~ Month

"Pre-assembly Inventory Adjustment"=
("Desired Pre-assembly Inventory"-"Pre-assembly Inventory")/"Pre-assembly Adjustment Time"
~ Lots/Month
Time to Adjust Finished Goods Inventory=
0.5
~ Month

Time to Update Channel Orders=
0.25
~ Month

LSMC Market Share=
LSMC Attractiveness/Total Attractiveness
~ Dmnl

Competitors Attractiveness=
0.3125
~ Dmnl

Reference Fraction Orders Filled=
0.8
~ Dmnl

Total Attractiveness=
Competitors Attractiveness+LSMC Attractiveness
~ Dmnl

LSMC Attractiveness=
Table for Attractiveness(Perceived LSMC Fraction Orders Filled/Reference Fraction Orders
Filled\
)
~ Dmnl

Table for Attractiveness(
[(0,0)-(2,2)],(0,0),(0.687059,0.24911),(1,1),(1.99529,1.08185))
~ Dmnl

Time to Perceive Fraction Orders Filled=
3
~ Month

****
.Control

**~
Simulation Control Parameters
|

FINAL TIME = 36
~ Month

INITIAL TIME = 0
~ Month

SAVEPER =
TIME STEP
~ Month

TIME STEP = 0.125
~ Month

Bibliography

Bronfenbrenner, M., W.Scichel and W. Gardner, *Microeconomics, 2^{nd} Edition*, Houghton Mufflin Company, Boston, 1987.

Closkey, C., *Developing Decision Processes for Managing Supply Chain Dynamics*, Master Thesis, Sloan School of Management and Engineering School, Massachusetts Institute of Technology, Cambridge, MA, 1998.

Cox, D., J. Little and D. O'Shea, *Ideals, Varieties, and Algorithms: An Introduction to Computational Algebraic Geometry and Commutative Algebra*, Springer-Verlag, New York, 1991.

Elberg, E., *A System Dynamics Approach to the Software Development Business Problem*, Master Thesis Sloan School of Management and Engineering School, Massachusetts Institute of Technology, Cambridge, MA, 2000.

Felch, J.A., *Supply Chain Modeling for Inventory Analysis*, Master Thesis Sloan School of Management and Engineering School, Massachusetts Institute of Technology, Cambridge, MA, 1997.

Ford, D.N., "A Behavioral Approach to Feedback Loop Dominance Analysis," *System Dynamics Review,* Vol. 15, no. 1, Spring 1999, pp. 3 – 36.

Forrester, N., *A Dynamic Synthesis of Basic Macroeconomic Policy: Implications for Stabilization Policy Analysis*. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1982.

Forrester, N., "Eigenvalue Analysis of Dominant Feedback Loops.", *Proceeding of the 1983 International System Dynamics Conference, Plenary Session Papers.* System Dynamics Society: Albany, NY, pp178-202.

Gaitonde, D.S., *Supply Chain Management*, DePaul University, Chicago, Illinois. URL: http://students.depaul.edu/~dgaitond/scm.htm

Gerwin, H.R. *A System Dynamics Study of Technology Strategy Implementation*, Master Thesis Sloan School of Management and Engineering School, Massachusetts Institute of Technology, Cambridge, MA, 2000.

Goncalves, P., C. Lertpattarapong and J. Hines, "Implementing Formal Model Analysis", *Proceeding of the 2000 International System Dynamics Conference, (to be published).*

Hines, J., *Molecules of Structure: Building Blocks fro System Dynamics Models*. Version 1.4, Leaptec, 1997.

Hines, J., *Analyzit software user manual*, Leaptec, 1999.

Hines, J., *Lecture Note: 15.875 System Dynamics and Applications, Spring 2000*, Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA, 2000.

Holt, C.M.T., *Supply Chain Simulator: An Approach for Development of Software and Methodology for Simulation of Supply Chain Management, developing*, Master Thesis, School of Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1999.

Kampmann, C.E., "Feedback Loop Gains and System Behavior." In: Richardson G.P. and Sterman J.D. (Eds.) *Proceeding of the 1996 International System Dynamics Conference Boston*. System Dynamics Society: Albany, NY, pp. 260-263.

Mojtahedzadeh, M.T. *A Path Taken: Computer-Assisted Heuristics for Understanding Dynamic Systems*. Unpublished Ph.D. Dissertation, Rockefeller College of Public Affairs and Policy, State University of New York at Albany, Albany NY, 1996.

Nagrath, I.J., M. Gopal, *Control Systems Engineering, 2nd Edition*, Wiley Eastern Limited, New Delhi, India, 1982.

Reinschke, K.J. *Multivariate Control: A Graph Theoretical Approach. Lecture Notes in Control and Information Sciences*. Berlin: Springer-Verlag. 1988.

Richardson, G.P. "Loop Polarity, Loop Dominance and The Concept of Dominant Polarity," International System Dynamics Conference, Oslo, Norway, August 1984.

Saleh, M., and P. Davidsen, *An eigenvalue approach to feedback loop dominance analysis in non-linear dynamic models*. Unpublished Paper, Information Science Department, University of Bergen, Norway, 2000.

Sterman, J.D., *Business Dynamics: systems thinking and modeling for a complex world*, McGraw-Hill, Boston, MA. 2000.

Vidyasagar, M., *Nonlinear Systems Analysis, 2nd Edition*, Prentice Hall, Englewood Cliffs, New Jersey, 1993.