# SILICON CYCLES:
# AN ANALYSIS OF THE PATTERNS OF GROWTH IN THE SEMICONDUCTOR INDUSTRY USING SYSTEM DYNAMICS METHODS

by
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Submitted to the Alfred P. Sloan School of Management
and the School of Engineering
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## Abstract

What is the cause of the patterns of growth that have occurred in the semiconductor industry? Is growth caused by economic cycles that effect the demand for electronic products? Does growth come from price erosion of semiconductors caused by cycles of over-capacity in the global industry? Is growth driven by declining cost per function due to the constant improvement in density and performance of semiconductor technology? This thesis attempts to quantify the contribution of each of these effects to the growth of the semiconductor industry. The technique used in this analysis is to develop a formal model of the global semiconductor industry using system dynamics techniques. The results of this model are compared with the historical record of semiconductor bookings (orders), billings (sales) and book to bill ratio.

The analysis shows that nearly half of the growth of the semiconductor industry is tied to economic growth patterns. The other half comes from continual improvements in the levels of density and performance achieved in silicon based products. This performance increase comes through a series of new generations of technology that have occurred in three year cycles. Throughout the 1980s, these technology generations were most evidenced by DRAM (Dynamic Random Access Memory) products whose densities increased by a factor of four with the introduction of each new generation.

There is ample evidence that semiconductor products, especially DRAMs are subject to the effects of commoditization within a technology generation. However, the analysis carried out in this thesis suggests that commoditization is not the main contributor to the growth of demand for semiconductor products. Instead, it is the continual growth in technology capability from generation to generation that is the engine of growth for the industry.

Several conclusions are drawn from this analysis. One is that when the pace of technology improvement slows, the semiconductor industry will become much more prone to experience cycles of capacity utilization. These cycles already affect commoditized industries such as steel and air travel. The severe over-capacity that occurred during 1984-85 and the resulting drop in DRAM prices shows that commoditization is possible in semiconductor manufacturing. It appears that in the mid 90s the newly industrialized nations of Southeast Asia are trying to take market share in DRAM away from Japanese manufacturers. This could lead to another cycle of over-capacity and price reduction in the worldwide semiconductor industry, especially DRAMs, that could slow the upward trend in average selling price of semiconductors that began in 1992.

Thesis Supervisor: Henry Birdseye Weil
Title: Senior Lecturer, MIT Sloan School of Management

# *Acknowledgments*

As with any writing project of this magnitude, the words written down on paper may be the product of one mind; but the ideas that shaped those words come from a lifetime of knowledge that is focused through the lens of learning into a single cohesive piece of work. Although many people helped me to form the ideas contained in this thesis, the fact that I had a chance to write it at all was due to the encouragement and support of several key people. First and foremost among my supporters was my wife Gloria. From our first discussion of the subject she encouraged me to apply to MIT even though it would mean that we would have to spend a year apart. I don't know what would have happened if my company had not agreed to sponsor my return to school after an absence of over twenty years. I do know that the immediate support of my boss Dick Bushroe and his boss Lance Mills was crucial in obtaining company backing for my year at MIT. I thank them for their efforts on my behalf.

The idea for doing a study of cycles in the semiconductor industry came to me as I was listening to a lecture by Professor Emeritus Jay Forester the founder of systems dynamics. I felt that if he could step up to modeling the economy of the entire world, I could handle a small subset such as the global semiconductor industry. Although Prof. Forrester was the inspiration for this work it was one of his students, my advisor Henry Weil, who was most influential in shaping the ideas contained in the pages that follow. Prof. Weil was a constant source of encouragement through the dark days of February when I began to doubt my own ability to scale the steep learning wall that I had tackled. His generosity with both time and ideas provided the lens through which my unfocused ideas on the dynamics of business cycles were bent into a cohesive image.

The rays of knowledge that I gathered through my advisor's lens came from many sources, but Kate Pittsley of Dewey Library deserves special recognition. The data she obtained from the Semiconductor Industry Association provided the key reference modes for the models that I developed. I am also indebted to fellow students Max Michaels, Dave Tottle and Vijay Varma for their generosity with ideas and data that helped to shape this thesis.

# How to Read This Thesis

Three causes of the growth cycles experienced by the semiconductor industry are analyzed in this thesis. These three causes are:

- Macroeconomic cycles
- Commoditization
- Technology Progression

The contribution of each of these effects to the overall volatility of the semiconductor industry is quantified through the use of systems dynamics models. A single model has been constructed which, through the use of switches, is capable of simulating any combination of the three causes under investigation.

Readers who are familiar with the semiconductor industry can skip Chapter 1, which provides industry background information. It is assumed that readers are familiar with system dynamics at a conceptual level. Most of Chapter 2 along with sections 3.1 and 3.2 of Chapter 3 deal with details of structuring and initializing the model. For readers who are interested in the results rather than the methodology, these sections can be skipped except for sections 2.2.1 and 2.2.2, which present the main causal loops that form the basis for the model.

The table below shows how the remaining parts of the thesis relate to the three causes of growth cycles under investigation.

| Effect | Discussed in section | Conclusions |
|---|---|---|
| Macroeconomic Cycles | 3.3 | 3.3.2 - Responsible for half of the growth, and slowdown in 1990-91. |
| Commoditization | 3.4 | 3.4.4 - Can not account for growth cycles. Inconsistent with historical data on book to bill ratio. |
| Technology Progression | 3.5 | 3.5.4 - Responsible for half of the cycles in growth. If pace of technology progression slows, commoditization effects will predominate. |
| Comparison of three effects | Chapter 5 | 5.2 - Implications for policy makers |
| Model limitations and extensions. | Chapter 4 | 4.1.3 - Inadequacy for forecasting |

The appendices provide detailed documentation of the system dynamics model used in the thesis. The model was created in Vensim, a commercially available system dynamics modeling system. Subsets of the model diagrams and equations are located throughout the thesis wherever they were thought to add clarity to the discussion. Anyone who seeks more detailed information about the construction of the model than is contained in the simplified diagrams of Chapters 2 and 3 will find it in the appendix.

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# 1. INTRODUCTION

## *1.1 Background*

Since the beginning of the integrated circuit industry in the early 1950s, the number of transistors which could be connected together on a single piece of silicon as a functioning electronic circuit has doubled every year and a half[1] reaching a density of greater than 64 million transistors/chip by 1995. No industry in the history of mankind has experienced as rapid a rate of productivity growth for as many decades as the semiconductor industry.

Semiconductors have become the battleground of international competition as industrialized nations have fought for market share with newly industrialized nations that are seeking to establish a technology base for high technology products that can be traded in world markets. Franco Malerba [Malerba 1985] chronicles the rise and fall of the semiconductor industry in Europe. He concludes that the close link between computers and semiconductors in the US allowed the US to take an early lead in digital integrated circuits, a lead that Europe was unable to overcome. Malerba also concludes that a strong demand for consumer products, coupled with a protectionist policy on the part of the Japanese government, allowed the Japanese industry to fight off the early onslaught of US-made digital ICs and regain a major share of the world market for very large scale integrated circuits. Michael Borrus [Borrus, 1988] defines the national significance of the US industry's eroding position in microelectronics. Borrus argues that microelectronics is not just an intermediate input industry like ball bearings. Instead, it is the source of economic and technological benefits that spur the economy and provide enormous social gains. Other authors have argued that foreign trade in semiconductors has consistently led to reduction of job opportunities in the US [Tyson, 1988]

Clyde Prestowitz [Prestowitz 1988] gives a detailed analysis of the DRAM (Dynamic Random Access Memory) crisis of the mid 1980s during which the Japanese succeeded in capturing over 65% of the world market for DRAM, and drove all but one of the US semiconductor manufacturers out of the DRAM business. During the DRAM crisis Japanese and US semiconductor suppliers suffered heavy losses when the price of DRAMs dipped below their production cost. US manufacturers lost $2 billion dollars and decided to exit the business. The

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[1] Gordon Moore of Intel Corporation first made this observation which has come to be known as Moore's Law. One simple formulation of Moore's Law is: Number of Transistors/Chip = $2^{(Year-1956)*2/3}$

Japanese manufacturers lost $4 billion[2] dollars during the same period, but stayed in the business and gained significant market share. When demand for DRAM outstripped capacity in the late 1980s, Japanese managers were reluctant to add DRAM capacity for fear of setting off another round of price wars. This led US companies such as Texas Instruments and Hewlett-Packard to set up joint ventures to manufacture DRAM overseas in order to prevent future shortages.

The importance of the semiconductor industry and the semiconductor equipment industry has lead to various forms of government assistance both within the US and abroad. In an attempt to level the international playing field, the US Congress passed legislation in 1986 authorizing the formation of SEMATECH (SEmiconductor MAnufacturing TECHnology). Funding for SEMATECH comes in part from its members, which are restricted to US companies and in part from the US Department of Defense. It was established in response to growing national concern over the United States' inability to compete evenly with international competitors in the manufacture of advanced integrated circuits. Concurrent with the establishment of SEMATECH, an adjunct organization called SEMI/SEMATECH was formed to serve as the main communications link between the SEMATECH headquarters and R&D facility in Austin and SEMATECH member companies. SEMI/SEMATECH seeks to continuously improve the relationship between users and suppliers of semiconductor manufacturing equipment. It is particularly focused on the rapid development and insertion of advanced semiconductor manufacturing technology.

The growth of the semiconductor industry has not been smooth. The industry has gone through periodic cycles of under and over capacity. These cycles have been driven by strategic international investments in semiconductor manufacturing (as was the case during the DRAM crisis) by fluctuations in supply and demand in the electronics industry, and by fluctuations in global economic conditions. The cost of building a state of the art integrated circuit fabrication facility has grown to the point that semiconductor companies such as Motorola, Texas Instruments and Intel Corporation have announced that they will spend over $1 billion[3] to build their next fab. A capital expenditure of this magnitude requires additional research and development expense in order to maintain a state of the art manufacturing processes for

---

[2] [Prestowitz, 1988], p. 69.

[3] Intel Corporation 1993 Annual Report, p. 1.

integrated circuits. Intel spent $930 million on R&D in 1993,[4] which represented 11% of their net revenues. Intel's total capital investment in plant and equipment in 1993 was $1.93 billion, which represented 22% of sales. This means that Intel spends nearly 1/3 of every revenue dollar on capital equipment and R&D in order to maintain their lead as the worlds foremost supplier of advanced microprocessors and associated integrated circuits.

Many people argue that reports of $1 billion investments for a single manufacturing plant are used as scare tactics to keep new entrants from entering the industry, but the fact remains that the semiconductor industry is an extremely capital intensive industry. The manufacturing equipment is not only expensive, but its useful life can be as short as three years. This has led to a recommendation that congress grant an exception to depreciation rules which would allow semiconductor equipment to be written off sooner than comparable equipment in other industries. Allowing depreciation of semiconductor manufacturing equipment in three years rather than five would increase the annual rate of semiconductor industry capital investment by 11 percent.[5] This would allow the US semiconductor industry to compete with other countries that have more favorable tax rules for high tech industries, and would slow the growth of US investments in foreign IC fabrication facilities.

Semiconductor manufacturing capability requires durable, specialized, untradable factors of production which have been referred to as sticky factors. [Ghemawat, 1991] Ghemawat argues that the key to the persistence of business strategy is management commitment to develop and maintain these sticky factors. His bottom line recommendation is that managers should figure out what key choices are important, and devote extra effort to getting those choices right. To build or not to build a new semiconductor manufacturing facility is clearly one of those key choices, as is the decision to upgrade an existing facility to use the next generation of semiconductor manufacturing equipment. These decisions are made in a national spotlight, and are often caught in a conflict between economic and national security.[6]

Throughout much of the history of the semiconductor industry, the development of new semiconductor processes and applications has been technology driven. Companies and countries

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[4] Ibid., p. 2.

[5] [NACS, 1990], p. 12.

[6] See [Prestowitz, 1988] for an excellent discussion of the role of national security in the US trade negotiations for high tech products such as machine tools and semiconductors.

fought to maintain leadership in state of the art semiconductor manufacturing processes. The investments required to maintain this technological leadership often came from profits in other businesses such as mainframe computers (IBM), communications (AT&T) or consumer electronics (Japan, Inc.). The emergence of the ASIC (Application Specific Integrated Circuit) business in the early 1980s provided a channel by which companies without semiconductor manufacturing facilities could acquire custom-built state of the art semiconductor components for their products. Fab-less semiconductor companies such as Weitek and Chips and Technologies emerged and became very profitable. Their strategy was to use the excess capacity of commercial and captive semiconductor suppliers to build products which served broad markets such as the growing market for personal computers. These new companies created new markets for advanced semiconductor technology. Companies with captive semiconductor facilities such as Hewlett-Packard and AT&T entered the ASIC business and began supplying a wide range of semiconductor products to customers other than their own internal divisions. By 1991 even IBM had entered the semiconductor OEM business. Many of the changes in recent years are moving the semiconductor business toward becoming market driven rather than technology driven.

As the cost of new semiconductor fabrication facilities has risen, the decision to maintain semiconductor captive fabrication facilities has come under more scrutiny. The availability of alternate suppliers for advanced ASICs has caused many smaller companies to exit the semiconductor business and seek partnerships with larger semiconductor manufacturers. The density and performance available from advanced semiconductor processes provided an incentive for producers of electronic products to build new ASICs in the latest processes. In the early 1990s this lead a shortage of manufacturing capacity in advanced semiconductor processes, even though there was excess capacity available in older processes.

## 1.2 Dynamic Hypothesis

This thesis will explore the interaction between three concurrent influences that effect the growth of the semiconductor industry.

1. Economic cycles which effect demand for semiconductor products.

2. International competition which produces cycles of over and under capacity which drive demand growth for semiconductor products.

3. Continual improvement in the cost per function of semiconductors due to the development of advanced semiconductor processes.

The dynamic hypothesis, simply stated, is that the growth in demand for semiconductors comes from not one, but a combination of the above factors.

This thesis will develop a system dynamics model of the semiconductor business, and use it to test the above hypothesis against historical data on demand for semiconductor products. The objective of this exploration is to explain the variations in the growth of the semiconductor industry, not to provide an exact match to historic data.

## *1.3 Literature Review*

There are many books written about the semiconductor industry, and about its strategic importance to the United States and other nations. Michael Porter in his work on the competitive advantage of nations [Porter, 1990] found that of the ten nations he studied three nations (US, Japan and Korea) had competitive positions in the export of semiconductor products. The US led the world in 1985 both in terms of its share of world exports of semiconductor products and in the share of its country exports made up of semiconductors. Since 1985 the US has lost its leading position to Japan, and regained it again. The bibliography lists a number of books which discuss the semiconductor industry, but none of these books give dynamic models to explain variations in the semiconductor industry over time.

A search of the system dynamics literature failed to produce any theses or models of either the semiconductor industry or the semiconductor equipment industry, it did however produce a couple of interesting theses that model related effects in other industries. A model of the decline of the US steel industry [Dansamasatid, 1992] produced some significant insights into the links between the decline of the US industry and the failure to adopt modern production technology. An analysis of business cycles in the US machine tool industry [Kallenberg, 1994] produced insights into how small changes in Gross Domestic Product are amplified along the capital equipment supply chain, causing a significant variation in incoming orders to the machine tool industry.

The concept of mass customization has been used in the ASIC industry from its inception. LSI Logic, one of the pioneering companies in the merchant ASIC market provides mass customizing of a form of ASICs called Gate Arrays. Gate Arrays were originally developed by IBM for use in manufacturing main frame computers. Gate Array manufacturing involves adding customizing metal layers to arrays of transistors (called base arrays) which are prefabricated on silicon wafers. The underlying base arrays are mass produced in quantity and then customized in small lots based on customer orders. Joseph Pine [Pine, 1993] has written the definitive work on mass customization, in which he has developed a number of dynamic feedback loops (also known as causal loop diagrams in system dynamics language) which explain the causes and limitations to growth of mass customization. Pine does not go beyond the causal loop diagrams to develop a dynamic model of the changes that the diagrams imply.

## 1.4 Sources of Data

The types of data which are needed to validate the dynamic hypothesis are the segmented sales of semiconductors worldwide, economic data, and data on the technological evolution of the semiconductor industry. Economic data is available from many sources. Changes in the consumer price index are available from the US Department of Commerce, Bureau of the Census. Changes in the Gross Domestic Product are available from the International Monetary Fund and the World Bank. The Federal Reserve Board provides data on a number of measures of production which can also shed light on economic fluctuations.

There is a fair amount of data on the semiconductor industry available in the public domain. The US Department of Commerce Bureau of the Census publishes data on the value of shipments of semiconductors which is segmented by technology (Bipolar and MOS), by circuit type (Logic/Microprocessor and Memory) and by circuit size within each segment. The Department of Commerce also publishes data on the aggregate capital expenditures for the electronic component industries, and on the value of shipments by semiconductor equipment suppliers. Import / export data on semiconductors is also available from the United Nations International Trade Statistics Yearbook (used by Michael Porter as the main source of information for his research on the competitive advantage of nations).

The most accurate source of data on semiconductor industry capital investment is in the form of semiconductor manufacturing equipment shipments. This data comes from commercial firms that specialize in providing such data to industry. One important source of data is VLSI Research Inc., a consulting company in San Jose, CA. The US Department of Commerce used VLSI Research Inc. data in its competitive assessment of the US semiconductor manufacturing equipment industry. [DOC/ITA, 1985] This led to the founding of SEMATECH. Other consulting firms which supply relevant data are Dataquest and ICE (Integrated Circuits Engineering). Data on world wide bookings (orders) and billings (shipments) of semiconductors has been tracked by the Semiconductor Industry Associates (SIA) since its inception in 1976 (see appendix for a listing of data sources). The SIA data will be used as the historical reference mode for validation of the models which are created.

# 2. Model Structure

## 2.1 Approach to Modeling

This thesis explores the hypothesis that growth of the semiconductor industry is driven by three main causes: economic cycles, price competition due to capacity utilization effects, and technology evolution. A series of models is developed in an attempt to understand the underlying causes which lead to the cycles observed in the world wide semiconductor industry. The purpose of each model is to explore the simplest structure which can explain the historical growth patterns which are observed. New structure is added to the model only when the present structure is determined to be inadequate to explain the historic variations.

## 2.2 Causal Loop Diagrams

### 2.2.1 Economic and Capacity Effects

Figure 2.1 shows the main causal loops involved in modeling capacity utilization and price effects. The same structure will be used to explore economic effects. In reinforcing loop R1, an increase in Capital Investment leads to an increase in manufacturing Capacity which in turn leads to a reduction in Capacity Utilization. Decreasing capacity utilization leads to lower Prices as manufacturers try to stimulate Demand. Lower prices lead to higher demand which leads to higher Revenue, higher Profits and greater Capital Investment. This reinforcing loop is counteracted by the effects of the balancing loop B1. Loop B1 is

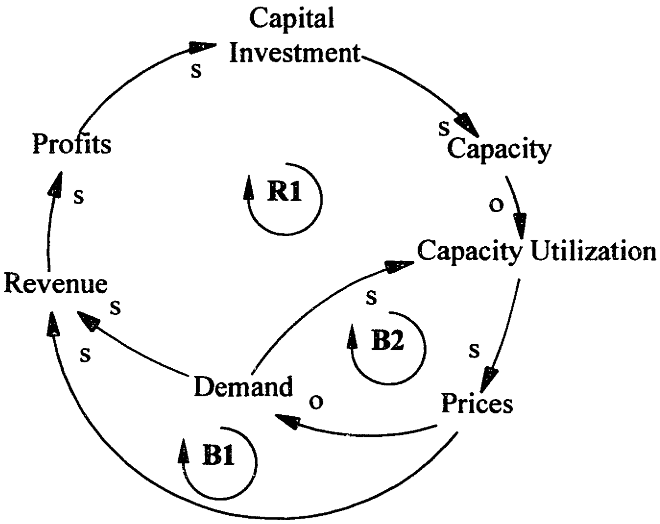

**Figure 2.1 - Capacity Utilization and Price Effects**

identical to R1 except for the link directly from prices to revenue. As prices drop, revenue drops which decreases profits and decreases capital investments. The second balancing loop B2 stabilizes prices because as prices drop demand increases which in turn increases capacity utilization which increases prices.

The interactions between price discounting (due to over-capacity) and demand growth in the semiconductor industry are the main structure of the model which is used to explore economic and capacity effects.

### 2.2.2 Technology Effects

Figure 2.2 shows the causal loop diagram used to model technology effects. In reinforcing loop R2, profits are used to fund research and development which leads to increased density and performance of semiconductor products. This technology improvement increases both the demand for newer products and the prices that semiconductor manufacturers can charge for their products. The increase in prices which comes with the new technology leads to reduced demand through loop B3. The amount of revenue growth which results from introduction of the new technology depends on the relative strength of the demand increase resulting from loop R2 and the demand reduction resulting from higher prices (loop B3). As an example, the price of DRAM at introduction has doubled with each new generation, while the density of each generation has increased by a factor of four. This means that the price per function (e.g. the cost per bit of DRAM) is decreasing even though the average

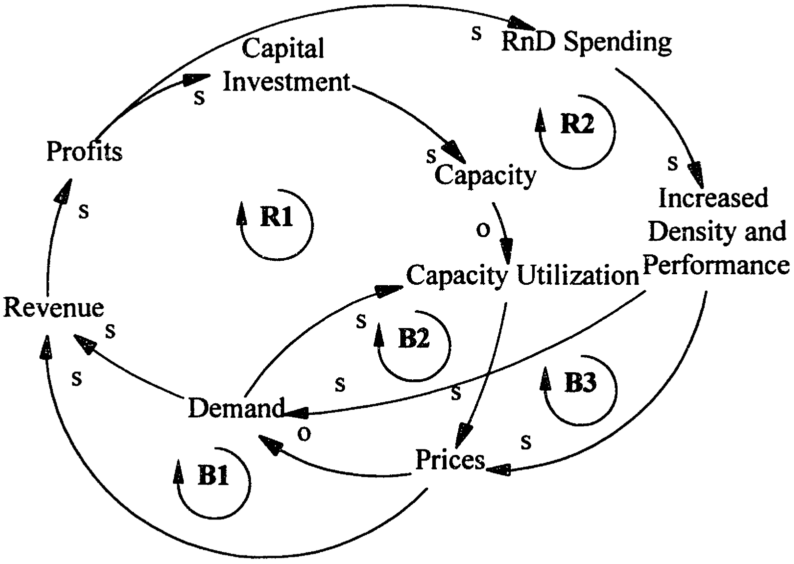

**Figure 2.2 - Causal Loops for Technology Effects**

selling price of DRAMs has risen. Thus the reinforcing loop R2 has a larger effect on demand growth than the balancing loop B3.

## *2.3 Overview of the Model*

A series of models are used in this thesis to test various theories of the growth dynamics of the semiconductor industry. As new structure was added to the model, switches were added so that the new features could be tested individually. This allows a return to earlier simple models by turning off the effects which have been added. The model has been constructed using the student version of Vensim, a system dynamics modeling program. A complete listing of the models developed for the thesis along with their stock and flow diagrams is shown in the appendix. Simplified stock and flow diagrams are used throughout the thesis to explain the model runs. In the simplified diagrams variables which are unimportant to the understanding of the model have been hidden from view.

## *2.4 Model Boundary*

The table below shows the variables which are calculated by the model (endogenous data) and the variables which are taken as inputs to the model (exogenous data). The variables marked with an asterisk (*) relate to the technology effects which are discussed in detail in section 3.5.

<table>
<tr><th colspan="2">Model Boundary</th></tr>
<tr><th>Endogenous Variables</th><th>Exogenous Variables</th></tr>
<tr><td>Actual Delivery Delay (for T1* and T2*)</td><td>Base Cost of New Capacity</td></tr>
<tr><td>Asset Life</td><td>Cost of New Capacity</td></tr>
<tr><td>Backlog (for T1* and T2*)</td><td>Density Performance of T1* (Vs R&D spend)</td></tr>
<tr><td>Book to Bill Ratio (for T1* and T2*)</td><td>Density Performance of T2* (Vs R&D spend)</td></tr>
<tr><td>Capacity (for T1* and T2*)</td><td>Fraction of R&D on T1*</td></tr>
<tr><td>Capacity Utilization (for T1* and T2*)</td><td>GDP Growth Rate</td></tr>
<tr><td>Capital Investment</td><td>Reference Price</td></tr>
<tr><td>Demand</td><td></td></tr>
<tr><td>Depreciation</td><td></td></tr>
<tr><td>Expenses</td><td></td></tr>
<tr><td>Fixed Costs</td><td></td></tr>
<tr><td>Industry RnD Spending*</td><td></td></tr>
<tr><td>Margin</td><td></td></tr>
<tr><td>Orders (for T1* and T2*)</td><td></td></tr>
<tr><td>Price (for T1* and T2*)</td><td></td></tr>
<tr><td>Profits</td><td></td></tr>
<tr><td>Property Plant and Equipment</td><td></td></tr>
<tr><td>Revenue</td><td>(* variable discussed in section 3.5)</td></tr>
<tr><td>Shipments (for T1* and T2*)</td><td></td></tr>
</table>

The table below lists the initialization parameters and reference data used in the model. The data listed as reference data is exogenous data, but is only used to check the results from model runs against the historic record.

| Initialization Parameters | Reference Data (exogenous) |
|---|---|
| Initial Book to Bill | Estimated Wafer Production |
| Initial Backlog Inflator | SIA Book to Bill |
| Initial Estimated Wafer Supply | SIA Orders |
| Normal Asset Life | SIA Sales |
| Pipeline Factor | World Semiconductor Demand Growth |

## 2.5 Model Architecture

The model is divided into a number of sectors based more on convenience of modeling than on underlying structure. The main sectors of the model are shown in Figure 2.3, followed by a brief description of the function of each sector. When the model is used to simulate GDP and capacity utilization effects only one distribution sector is active and industrial R&D spending (calculated in the main sector) is included in profits. There are only two distribution sectors in the model because of the decision to model only one technology transition. This decision is discussed in

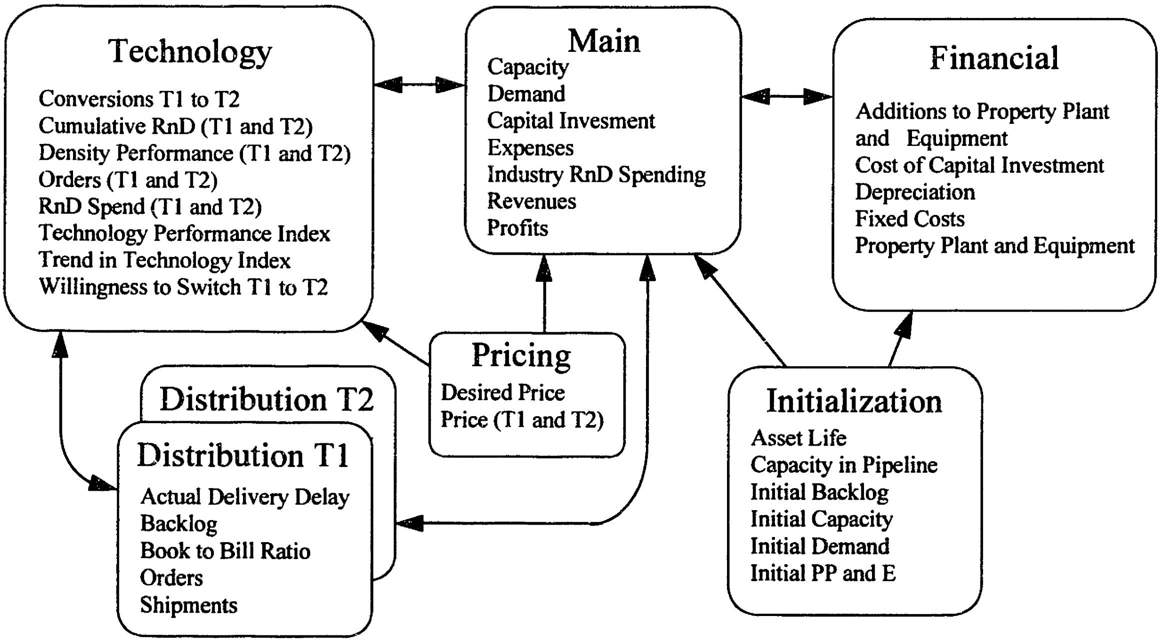

**Figure 2.3 - Architecture of Model**

detail in section 3.5. Extension of the model to include multiple technology sectors is straightforward, and is discussed more fully in section 4.2.

| Module | Function |
|---|---|
| Main | Contains the main causal loop of the model, calculates capital investment, expenses, revenue, and profits |
| Financial | Tracks total Property Plant and Equipment and calculates depreciation expense and fixed costs |
| Distribution | Tracks backlog and calculates orders, shipments and book-to-bill ratio |
| Initialization | Calculates a consistent set of initial conditions from initialization data |
| Pricing | Tracks price adjustments |
| Technology | Tracks cumulative effect of R&D technology improvement, and the resulting customer preference for technologies T1 and T2. |

# 3. Simulation Results

## 3.1 Reference Data

The reference period used as a base with which to compare the model output to historical data is the period from January of 1980 through December of 1993. The main source of reference data is the world wide semiconductor bookings (orders), billings (sales or revenue) and book to bill ratio. This data has been tracked since 1976 by the Semiconductor Industry Association. The SIA gathers data from semiconductor companies worldwide, and reports the data monthly and yearly to members of the association. Over the period since 1976, the accuracy of the data has improved as Europe, Japan, and most recently Korea and other Asian countries have begun to actively participate in data gathering. The granularity of the data has also improved as new categories such as micro-processors, standard cells and gate arrays have been reported separately. The overall structure of the SIA data is shown in Figure 3.1.

<table>
<tr><td colspan="7">Total Semiconductor<br>$77.3 Billion</td></tr>
<tr><td colspan="6">Integrated Circuits (ICs)<br>$66.0B</td><td>Discretes<br>$11.3B</td></tr>
<tr><td colspan="5">Digital<br>$55.4B</td><td>Analog<br>$10.7B</td><td></td></tr>
<tr><td colspan="4">Metal Oxide Semiconductor (MOS)<br>$52.4B</td><td>Bipolar<br>$3.1B</td><td colspan="2"></td></tr>
<tr><td colspan="2">Memory<br>$21.3B</td><td>Micro-processor<br>$19.1B</td><td>Logic<br>$12B</td><td colspan="3"></td></tr>
<tr><td>DRAMs<br>$13.1B</td><td>Other<br>$8.2B</td><td colspan="5"></td></tr>
</table>

**Figure 3.1 - Structure of SIA World Semiconductor Trade Statistics data in 1993**

In order to initialize the model on January 1980, the size of the semiconductor industry in 1979 is taken as a basis. The structure of the SIA data in 1979 is shown in Figure 3.2. Many fewer categories were reported in 1979, and only bookings and billings of the US semiconductor manufacturers were reported.

Figure 3.3 shows the SIA world wide total semiconductor bookings, billings and book to bill ratio for the period from January of 1978 through December of 1993 as reported by the SIA. All of the simulation runs begin in 1980. The data before 1980 is useful for model initialization because it shows that the book to bill ratio was greater than one for the two years prior to the start of simulations.

<table>
<tr><td colspan="6">Total Semiconductor<br>$6.62 Billion</td></tr>
<tr><td colspan="5">Integrated Circuits (ICs)<br>$4.67B</td><td>Discretes<br>$1.94B</td></tr>
<tr><td colspan="3">Metal Oxide Semiconductor (MOS)<br>$2.4B</td><td>Bipolar<br>$1.35B</td><td>Linear<br>$0.93B</td><td></td></tr>
<tr><td>Memory<br>$1.28B</td><td>Micro-<br>processor<br>$0.36B</td><td>Logic<br>0.7B</td><td></td><td></td><td></td></tr>
</table>

**Figure 3.2 - Structure of SIA data for the US Semiconductor Industry, 1979**

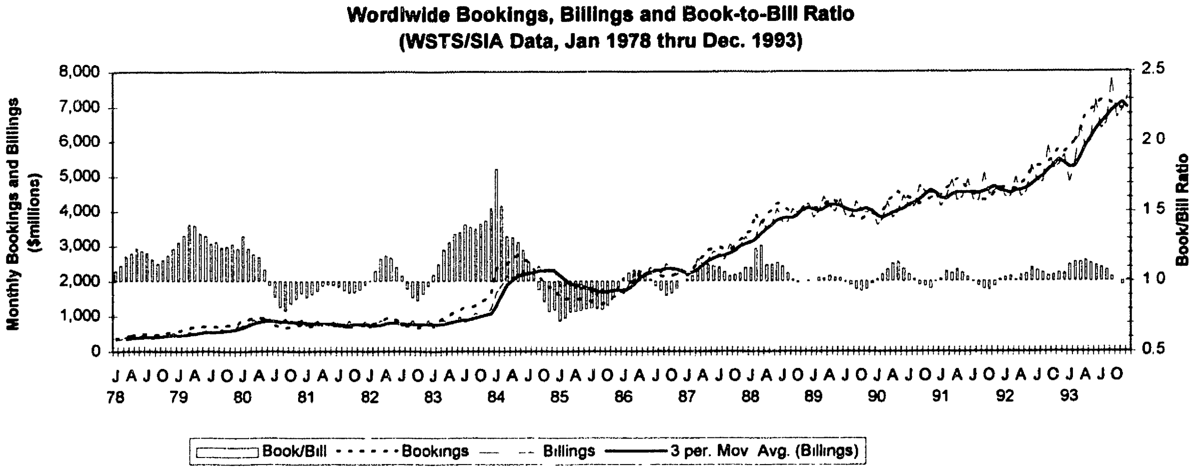

**Figure 3.3 - Worldwide Semiconductor Industry Bookings, Billings, and Book to Bill**

The data shown in Figure 3.3 is compiled from the SIA data listed in the appendix. Prior to 1980, only the bookings and billings of US manufacturers were reported by the SIA. In 1980 European manufacturers were added to the US data, and in 1984 Japanese manufacturers were added to the US and European data. In 1988 estimates for Korean based manufacturers were added, and in 1992 Asia Pacific and Other-based manufacturers were added. The worldwide semiconductor sales used as a reference mode in the model have been adjusted to include the Japanese manufacturers in the data prior to 1983. This has been done by using the market share data reported by the SIA. Sales equivalent to the Japanese market share have been added to the SIA-reported data between 1980 and 1993.

## 3.2 Model Initialization

In order to initialize the model, a number of parameters must be estimated from the SIA data. Many of these parameters are interrelated, and can be calculated using some simplifying assumptions. The table below gives the units and values used for initialization of the model.

| Parameter | Units | Initial Value |
|---|---|---|
| Initial Estimated Wafer Supply | KWS (Thousands of wafer starts) per year | 12,792 KWS/yr |
| Initial Capacity | KWSM (Thousands of 6" equivalent wafer starts per month) | 1066 KWSM |
| Base Cost of New Capacity | $ million/KWSM | 10 M$/KWSM |
| Initial PP&E (initial cost of installed Property, Plant and Equipment) | $ million | 10,660 M$ |
| Initial Book to Bill | Dimensionless ratio | 1.20 |
| Initial Demand | KWS per year | 15,350 KWS/yr |
| Initial Backlog Inflator | Dimensionless | 1 |
| Target Delivery Delay | Years | 0.25 yr |
| Initial Backlog | KWS | 3,838 KWS |
| Normal Asset Life | Years | 6.25 yr |
| Pipeline Factor | Dimensionless | 1 |
| Capacity in Pipeline | KWSM per year | 170.56 KWSM/yr |
| Reference Price | $ million/Thousand 6" wafers | 0.848 M$/KWS |
| Initial RnD on T1 | $ million | 1,500 M$ |

### 3.2.1 Estimating the Reference Price

One simplifying assumption which is used for modeling economic and capacity utilization effects is that the price of silicon per unit area is constant over the simulation period, and varies only due to the effects of under and over capacity in the industry. Figure 3.4 shows the variations in the average selling price (ASP) of semiconductors over the simulation period. The ASP for total semiconductors has varied around $0.40 reaching a low of $0.29 in 1985 and trending upward to $0.50 in 1993. The ASP of discretes has trended downward from $0.20 in 1980 to $0.10 in 1993 while the ASP of ICs has moved upwards from around $1.00 in the 83-84 time frame to $1.75 in 1993. These trends are consistent with advances in technology which have produced finer geometries (and thus smaller discrete devices) while allowing more functionality (and thus more value) to be integrated into an IC. A simplifying assumption of constant average price per unit area of silicon assumes that the reduction in area of discrete devices balances out any increase in area of ICs over the period.

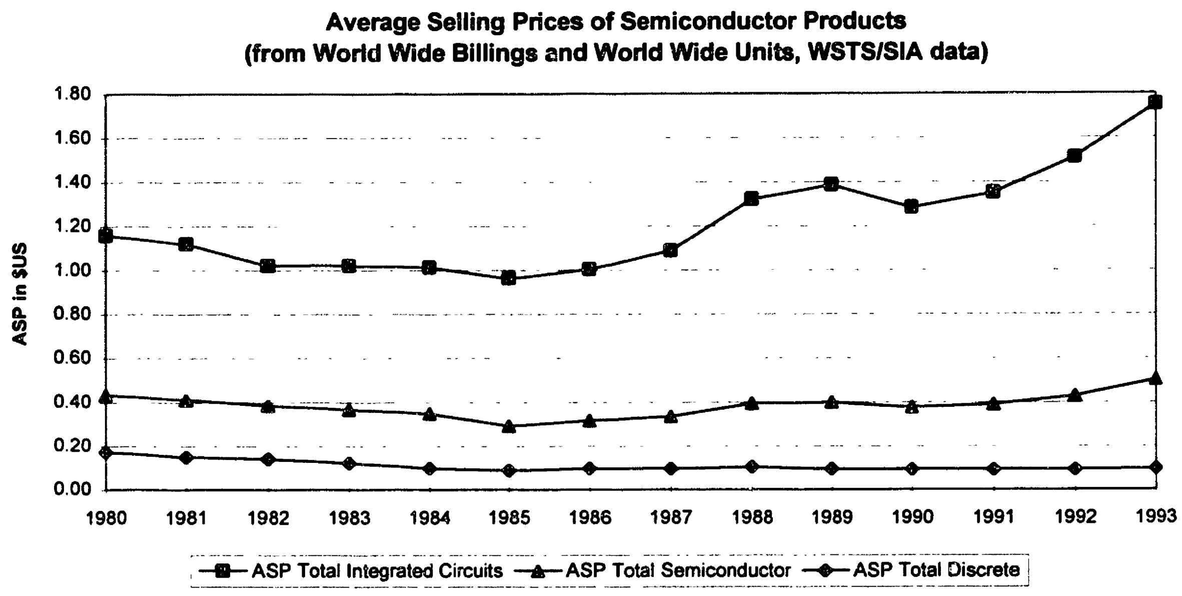

**Figure 3.4 - Average Selling Price of Semiconductors**

### 3.2.2 Expenses and Profits

Calculation of expenses and profits are based on assumptions about financial ratios which apply to the global semiconductor industry. The assumptions are that there is a target profit margin which is used to judge the health of the industry, that variable costs are proportional to wafer shipments and that fixed costs are the sum of depreciation of property plant and equipment and other fixed costs which depend on the amount of capacity installed. These expenses are initialized by applying financial ratios to the world wide semiconductor revenue. The financial ratios were estimated from Intel's 1993 annual report data, and are shown in the table below along with the model variables which are derived from them. The world semiconductor revenue in 1979 is derived from the US data shown in Figure 3.2 divided by the US market share in 1980 which equaled 61% of the world market.

Estimation of financial ratios for model initialization

| | Intel's '93 ratio | 1979 SIA data | Model Variable | Variable Value |
|---|---|---|---|---|
| Total Revenue | 100% | $10,846 M | Revenue | Calculated by the model |
| Net Income | 26% | $2,820 M | Target Margin | 0.26 |
| Variable Costs | 34% | $3,688 M | Base Variable Cost per KWS | 0.228 M$/KWS |
| Depreciation | 16% of PP&E | $1,706 M | 1/Asset Life | 0.16 %/yr |
| Other Fixed Costs | Total Revenue - Net Income - Variable Costs - Depreciation | $2,632 M | Fixed Cost per KWSM of Capacity | 2.5 M$/ (KWSM*yr) |
| Research and Development | 11% | $1,198 M | Fraction of Revenue to RnD | 0.11 |

Intel's variable costs were estimated from their total employee costs as a fraction of total sales. To insure consistency in the model, the other fixed costs are what is left after subtracting Net Income, Variable Costs and Depreciation from the Total Revenue.

Intel's 1993 financial ratios are among the best in the industry, and their level of net income is matched only by Micron Technology. When technology effects are added to the model, the research and development costs are subtracted from net income by reducing the target margin to 15%. This is closer to the average net margin of the top

Net Margin (Net Income / Net Sales) for Semiconductor Manufacturers with Net Income greater than $100,000 in 1993

| Company | Net Margin |
|---|---|
| Advanced Micro Devices | 14% |
| Intel | 26% |
| Micron Technology | 25% |
| Motorola | 6% |
| National | 12% |
| SGS Thomson | 8% |
| Texas Instruments | 6% |
| Average | 14% |

six semiconductor suppliers as shown in the table below.

### 3.2.3 Initializing Backlog

In order for the model to start up smoothly without undue transient effects it is necessary to take into account the effect of backlog buildup and capital investment which occurred prior to the start of the simulation. The SIA did not track industry backlog in 1980, nor did it track capital investments in the semiconductor industry. Figure 3.5 shows a simplified model of the relationship of backlog, orders, shipments and book to bill ratio. Backlog is a stock which accumulates the difference between two rates, the rate of incoming Orders and the rate of outgoing Shipments. The book to bill ratio is the ratio of Bookings (Orders) to Billings (Shipments). In the simple model in Figure 3.5, Shipments are constant at 5 units/year. Orders are constant at 5 units/year up until Time = 4 at which point orders begin to oscillate. The Book to Bill ratio starts out at 1 because orders equal shipments. Between Time = 4 and Time = 6 Orders exceed Shipments, the Book to Bill ratio is greater than one, and backlog is increasing. Between Time = 6 and Time = 8 Shipments exceed Orders and backlog is decreasing. The points (Time = 4 and Time = 10) at which the Book to Bill ratio switches from being greater than 1 to being less than 1 corresponds to the points of maximum backlog. The SIA data shows that the industry Book to Bill ratio was greater than 1 throughout the two years preceding 1980, and

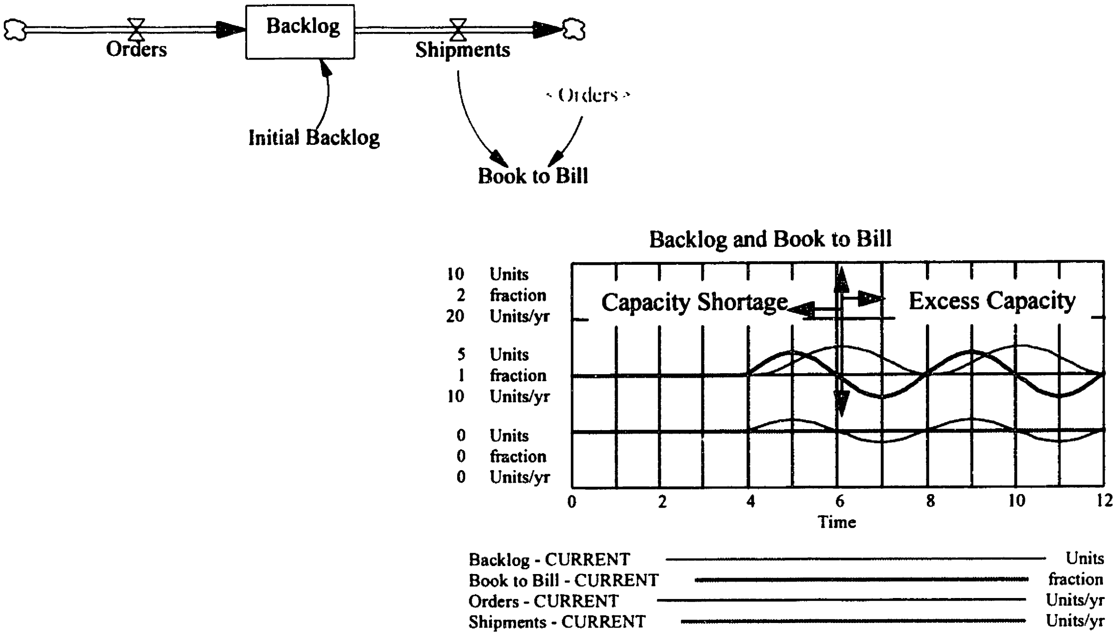

**Figure 3.5 - The relationship between Backlog, Orders, Shipments and Book to Bill Ratio**

crossed over to being less than 1 in mid 1980. This means that the industry backlog was near a maximum in January of 1980. There is no way to know how large the backlog was, but the Initial Backlog Inflator variable is used to adjust the Initial Backlog in the model so that the model output more accurately tracks the historical book to bill ratio shown in the SIA data.

### 3.2.4 Initializing Capacity Acquisition

In the model, the Capacity From Investment is simply the Capital Investment delayed (through a third order delay function in Vensim) by the Capacity Acquisition Delay. In order to take into account any capacity which was ordered (but not yet brought on line) before the model initialized, the model uses Vensim's DELAY3I function which allows the capacity pipeline to be initialized. The model variable Capacity in Pipeline is initialized to the Initial Capacity times a Pipeline Factor divided by the Asset Life. This represents the amount of capacity which will be retired each year. The variable Pipeline Factor is used to adjust the initial capacity injected into the system in order to more accurately match the SIA data.

## 3.3 Modeling Economic Effects

The first runs of the model will be used to test that the model behaves as expected. The variable in the model which controls demand is Demand Growth. Demand Growth is measured in %/year and represents the annual rate at which demand for semiconductors increases (or decreases). A simplified stock and flow diagram for these model runs is shown in Figure 3.6.

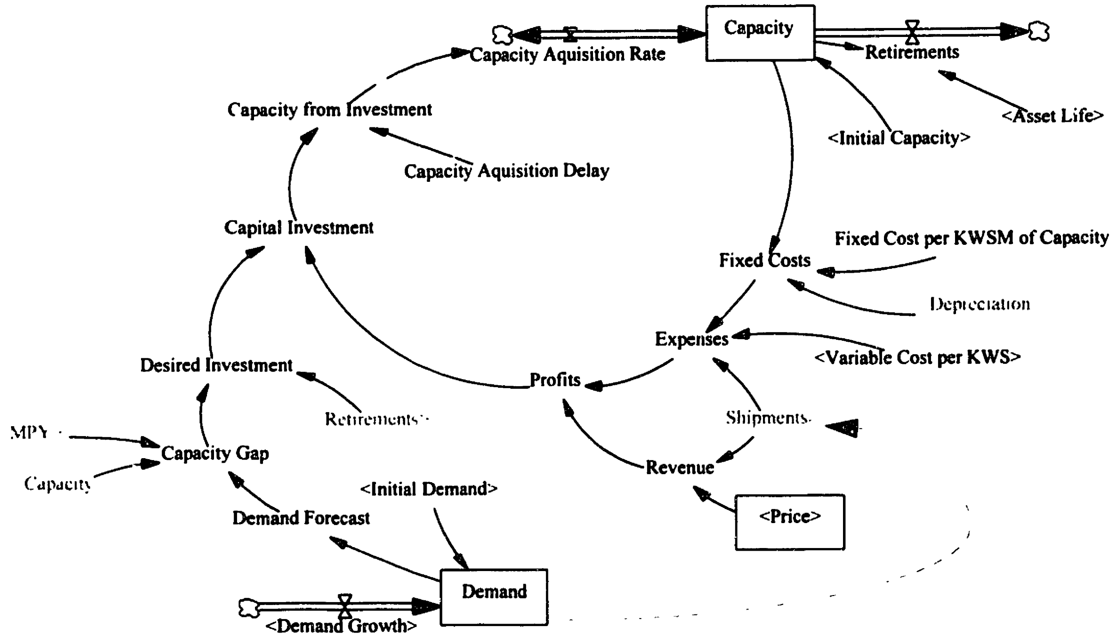

**Figure 3.6 - Simplified Stock and Flow Diagram for Initial Model Runs**

In this diagram, only the top level loops are shown. Demand is linked to shipments in a separate diagram, (the link is represented by a dashed arrow in Figure 3.6) but for these early runs of the model Backlog is turned off, and Shipments are a first order smooth of Demand. Demand Growth over the period of interest can be estimated by fitting an exponential growth curve to the historical data. As shown in Figure 3.7, the average growth from 1980 through 1993 is 14.9% per year.

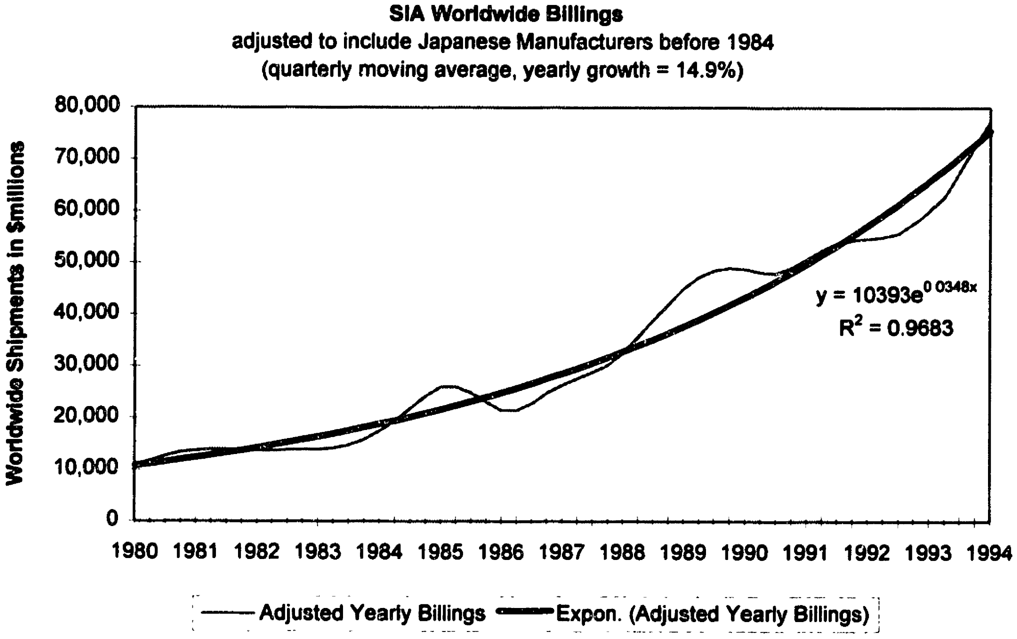

**Figure 3.7 - Demand Growth for the Semiconductor Industry Estimated from SIA Sales Data**

Setting Demand Growth in the model to 0.149 and running the model with no other effects turned on yields the output shown in Figure 3.8. The model behaves as expected with the Revenue growing exponentially over the period. As can be seen from the figure, the growth of the semiconductor industry has not been smooth. The growth increased sharply in the 1984-85 time frame and again in 1989 and 1993. Revenue growth actually decreased in 1985 and again in 1990. A possible explanation for these revenue variations is that Demand Growth is tied to the overall economic growth and varies with the GDP of the consuming countries. Since the US is the largest consumer of electronic products, it is reasonable to use the US GDP growth numbers as a proxy for world economic growth over the period.

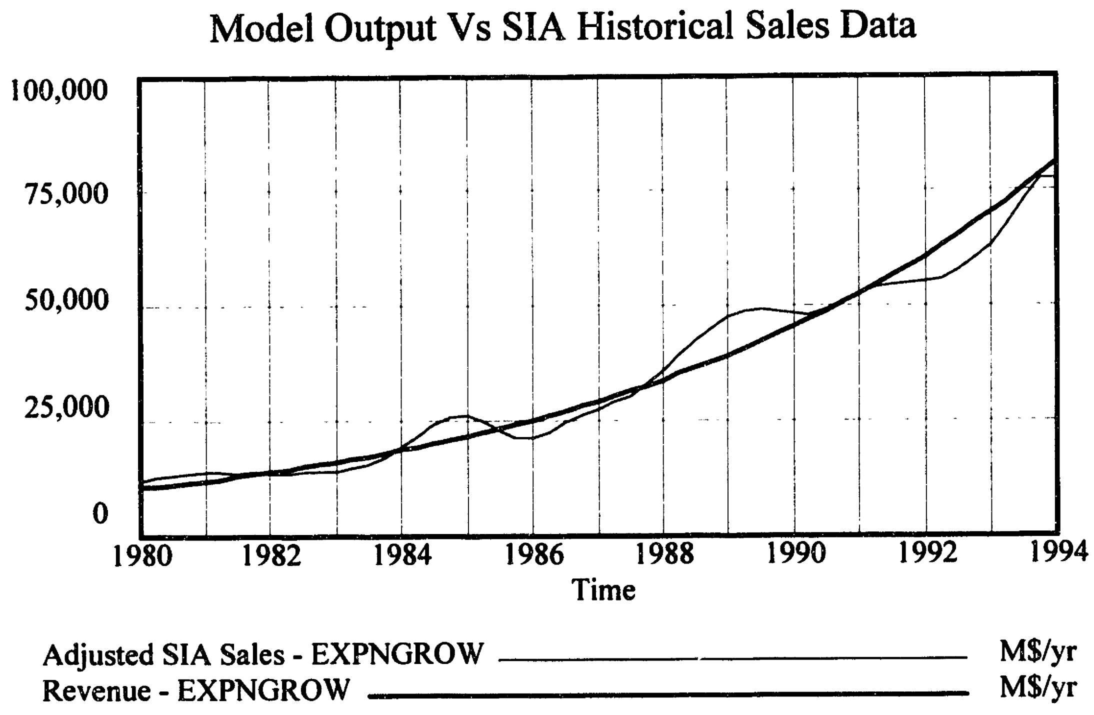

**Figure 3.8 - Model Output with Demand Growth set to 14.9%/year.**

### 3.3.1 Estimating the Semiconductor Growth Multiplier

The SIA tracks growth of the world wide semiconductor industry. Figure 3.9 shows the SIA growth data along with US GDP growth data obtained from the World Bank and the IMF.

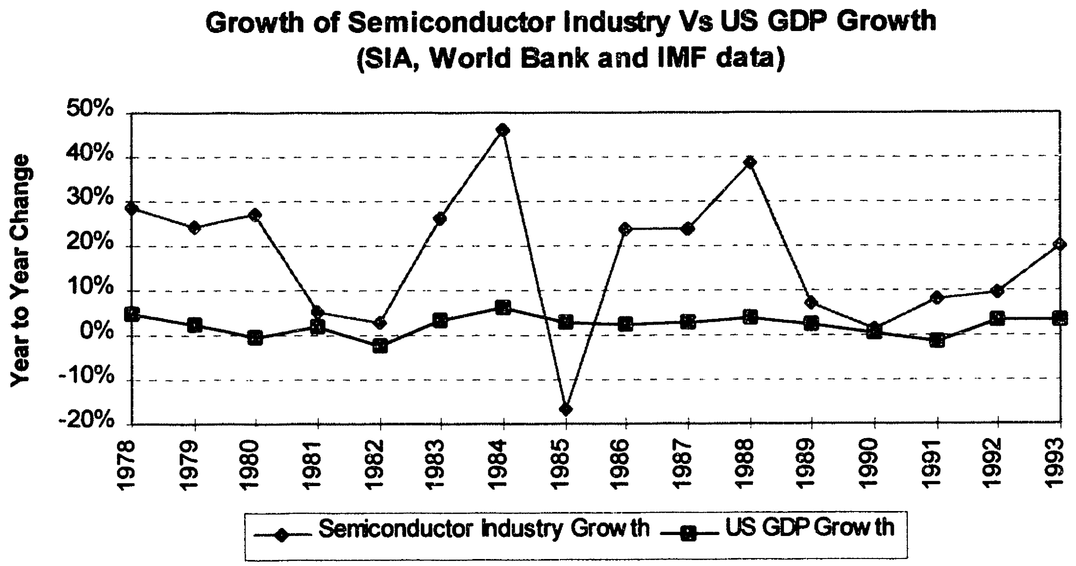

**Figure 3.9 - Semiconductor Industry Growth Vs US GDP Growth**

As can be seen from Figure 3.9, the GDP growth varies from a low of -2% in 1982 to a high of 6% in 1984 while the semiconductor industry growth varies from a low of -17% in 1985 to a high of 46% in 1984. There is some correlation between the two growth rates, but the correlation is weak. Figure 3.10 shows that the best fit correlation between semiconductor industry growth and the US GDP growth yields a multiplier of 3.56, i.e. the semiconductor industry growth is approximately 3.56 times the US GDP growth.

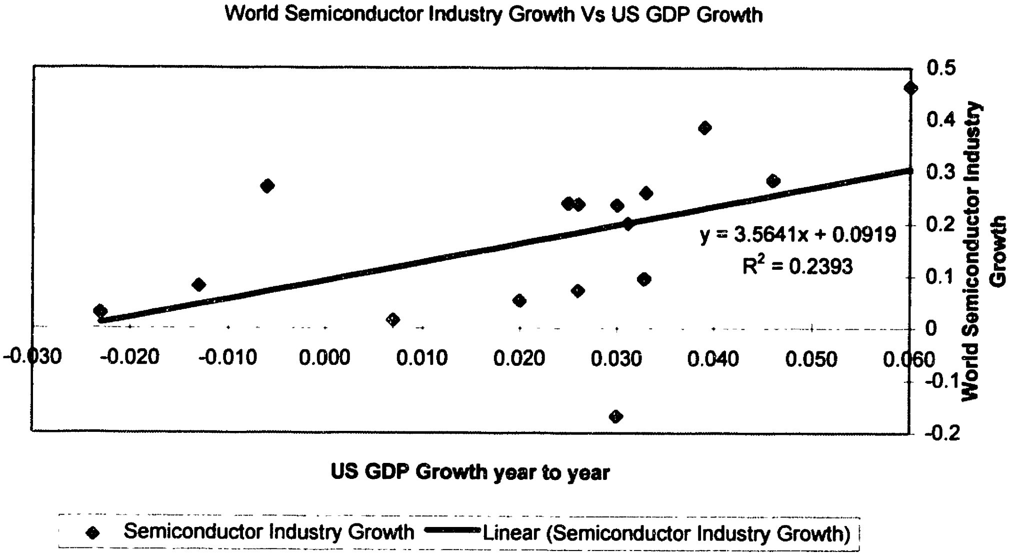

**Figure 3.10 - Correlation between Semiconductor Industry Growth and US GDP Growth**

The average US GDP growth over the period from 1980 to 1993 is approximately 2.1%. Applying the semiconductor industry multiplier of 3.56 yields an expected growth rate of 7.6% for the semiconductor industry. Figure 3.11 shows the model output when the Base Rate of Demand Growth is set to 7.3% and the GDP Growth Multiplier is turned on. This results in an average growth rate of 14.9% over the period. As can be seen from Figure 3.11, the GDP variations do slow semiconductor growth in the 1982-3 time frame and again in 1991-92, which were periods of recession in the US. However, GDP growth alone does not explain the rapid buildup of demand in 1984 or the revenue declines in 1985 and 1989-90. We will have to expand the scope of the model to explain these effects.

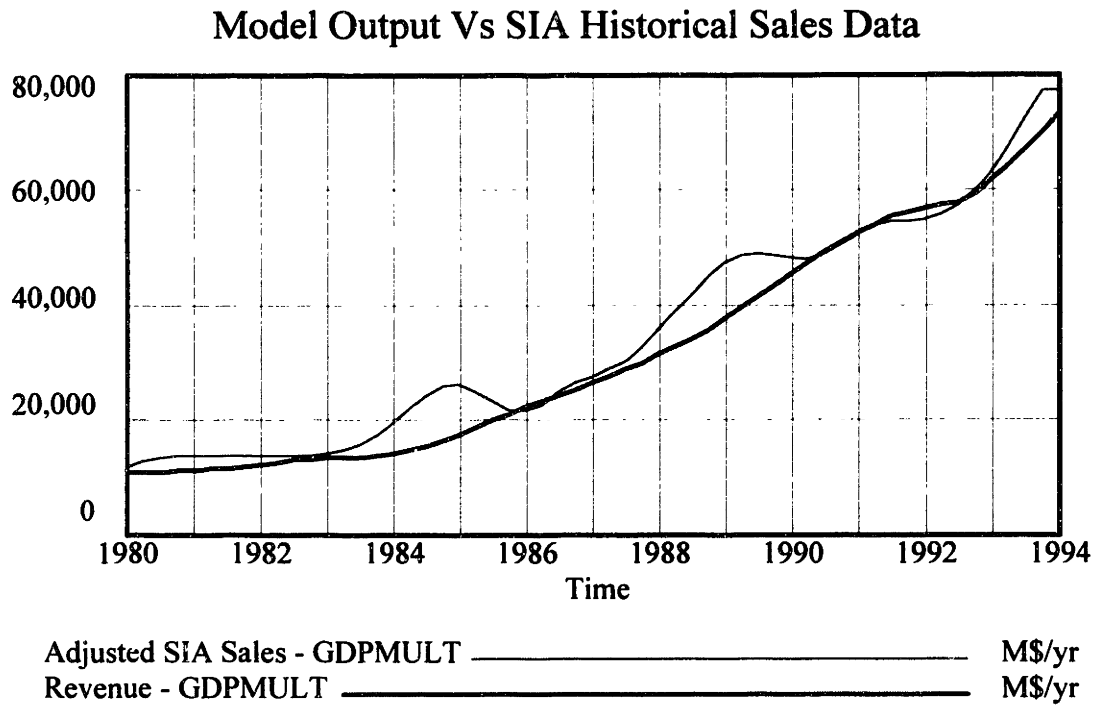

Figure 3.11 - Model output with Demand Growth driven by the GDP Multiplier

### 3.3.2 Conclusions from Modeling Economic Effects.

The GDP multiplier effect can account for abut half of the demand growth experienced by the semiconductor industry since 1980. However GDP growth alone cannot explain the cycles that the semiconductor industry experiences. We must look to other causes to explain both the high growth experienced in 1984 and 1993 and the contraction or low growth seen in 1985, and 1989. The second part of the dynamic hypothesis is that price reductions due to over-capacity produce the cycles of growth experienced by the semiconductor industry. This hypothesis will be explored in the next section.

## *3.4 Modeling Capacity Utilization Effects*

In order to model the effects of capacity utilization on industry revenues, we have to enable the portion of the model which deals with price changes. The stock and flow diagram which computes price is shown in Figure 3.12. The Price (measured in $ million per thousand 6" equivalent wafers) is adjusted to match the Desired Price over a Price Adjustment Time. The Desired Price is calculated from the Reference Price multiplied by the Capacity Utilization Effect on Price and the Effect of Delivery Delay on Price. Capacity Utilization is simply the ratio of Shipments to Capacity (multiplied by a conversion factor, MPY, which adjusts Capacity expressed in thousands of wafer starts per month to Shipments expressed in thousands of wafer starts per year).

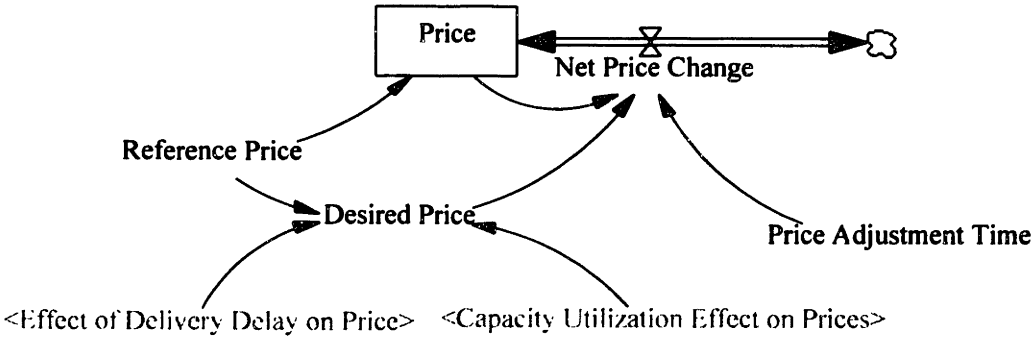

**Figure 3.12 - Stock and Flow Diagram for Determining Price**

When Backlog is turned on, Shipments are set to the minimum of the Desired Shipments and Capacity where Desired Shipments are Orders smoothed through the Backlog stock. This means that when Backlog is turned on, Shipments can never exceed Capacity, so Capacity Utilization (Shipments divided by Capacity) can never exceed one. When Orders exceed Capacity, the Actual Delivery Delay begins to rise above the Target Delivery Delay due to the effects of Backlog. The Effect of Delivery Delay on Price adjusts the Desired Price upward when the Delivery

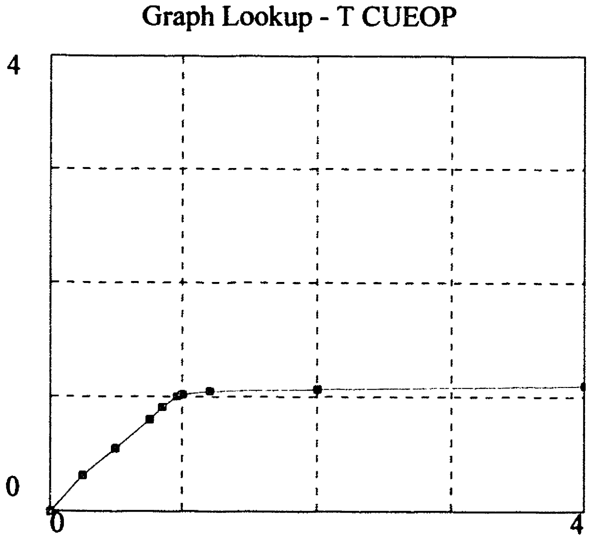

**Figure 3.13 - Capacity Utilization Effect on Price**

Delay relative to target exceeds 1, and the Capacity Utilization Effect on Prices adjust the Desired Price downwards when Capacity Utilization is less than one. Both of these effects use the table function CUEOP (shown in Figure 3.13) to compute the relative changes. The policy assumption underlying Figure 3.13 is that IC manufactures will reduce prices sharply to try to stimulate demand as soon as Capacity Utilization drops below about 0.95, but they will not be able to raise prices very much when Capacity Utilization exceeds 1 (or Delivery Delay exceeds Target Delivery Delay) in fear of loosing customers. When Backlog is turned off, Shipments are not limited by Capacity, and the Delivery Delay relative to Target is always 1. In this case all price changes occur through the Capacity Utilization Effect on Price.

The diagram in Figure 3.14 shows how Demand Growth is calculated when price effects are turned on. When the price effect is enabled (by setting SWPriceEffect to 1) the Demand Growth is the sum of a Base Rate of Demand Growth plus the Price Effect on Demand Growth. The Base Rate of Demand Growth is set to 7.6%, the average growth rate resulting from GDP multiplier effects. The Price Effect on Demand Growth is determined by the table function shown in Figure 3.15, indexed by the ratio of Price to Reference Price.

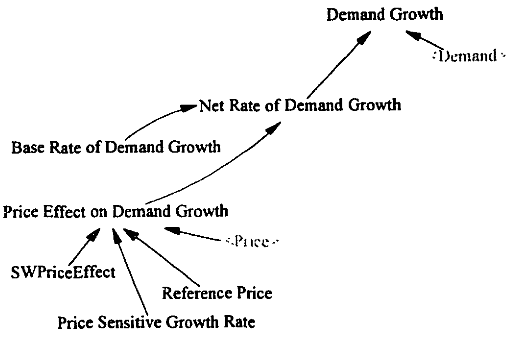

**Figure 3.14 - Factors in Determining Price Effects on Demand Growth**

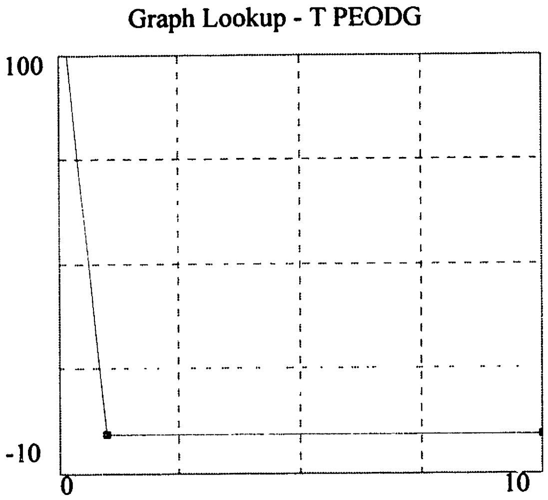

**Figure 3.15 - Price Effect on Demand Growth**

The Price Effect on Demand Growth determines the price elasticity of demand of semiconductors. Price elasticity is an economic concept that describes how a market reacts to changes in the price of a good. When the price elasticity of demand is greater than 1 (i.e. demand is elastic) a small reduction in price increases total spending on the good. When price elasticity is less than one, (i.e. demand is inelastic) a small reduction in price reduces total spending on a good.

VLSI Research, Inc. has estimated the long-run price elasticity of demand for DRAM to be nearly 7000 [VLSI Research Inc., 1994]. This means that the demand for DRAM increases by a factor of seven thousand bits for every one cent drop in DRAM price per Kilobit. However, in the short run, demand for semiconductors is highly inelastic because a drop in prices is not readily translated into increased demand for electronic products. The short-run price elasticity of demand for 64K DRAMs in 1985 was found to be 0.083. This means that manufacturers attempts to boost capacity utilization by lowering prices ended up reducing total revenues. VLSI Research Inc. estimates that every additional fab module brought on line in 1985 reduced the absolute size of the DRAM market by $545 Million.

In order for capacity utilization effects to account for half of the growth that the semiconductor industry has experienced over the period of interest, demand must be elastic. In order for industry revenues to decline, as they did in 1985, demand must be inelastic. Elasticity of demand is modeled by the Price Effect on Demand Growth as shown in Figure 3.15. When Price equals Reference Price the Price Effect on Demand Growth is zero and there is no effect on Price. When Price declines below Reference Price, the Price Effect on Demand Growth will be greater than one and Demand will grow. When price rises above Reference Price the Price Effect on Demand Growth will be negative, Demand will be inelastic, and both Demand and Revenues will decline.

### 3.4.1 Capacity Utilization and Price Effects

Turning on the price effects links changes in capacity utilization to Price and changes in Price to Demand (through changes in Demand Growth). These links are indicated by the dashed lines connecting Capacity to Price and Price to Demand in the stock and flow diagram shown in Figure 3.16. The link from Demand to Shipments is shown because Demand effects Shipments independent of Price effects.

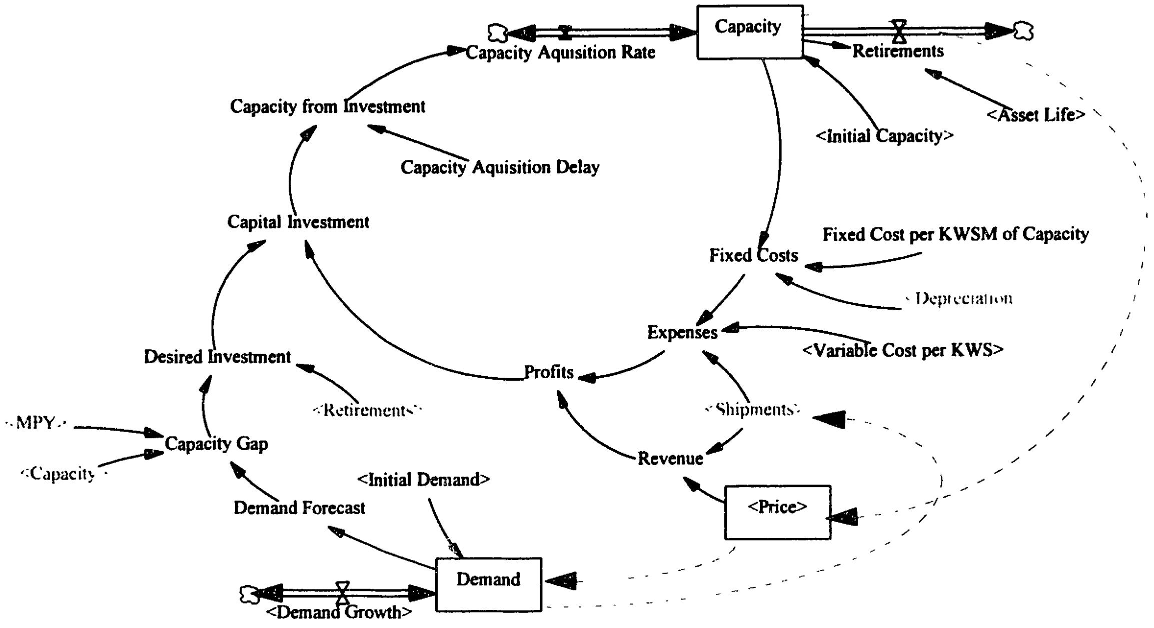

**Figure 3.16 - Stock and flow diagram for Price Effects due to Capacity Utilization**

The model output in Figure 3.17 is the result of turning on price effects. In this model run, price effects were turned on and the GDP effect was turned off in order to isolate the contribution of these two effects. The Base Rate of Demand Growth was set to 7.6% to produce the same average growth that the GDP multiplier would add if it were turned on. As can be seen Figure 3.17, the price effects produce significant demand growth which occurs in cycles spaced about three years apart. This growth is due to price discounting as a result of over-capacity in the industry. This model output begins to show the kind of industry cycles exhibited by the SIA data, however the timing and magnitude of the growth is off, especially in 1991 and 92. There is also no decline in revenues in 1985 due to the fact that demand in the model is elastic in 1985 (i.e. any price reduction leads to an increase in demand which is sufficient to offset the loss of revenues due to the price decrease) whereas historically we know that demand was inelastic in 1984-86.

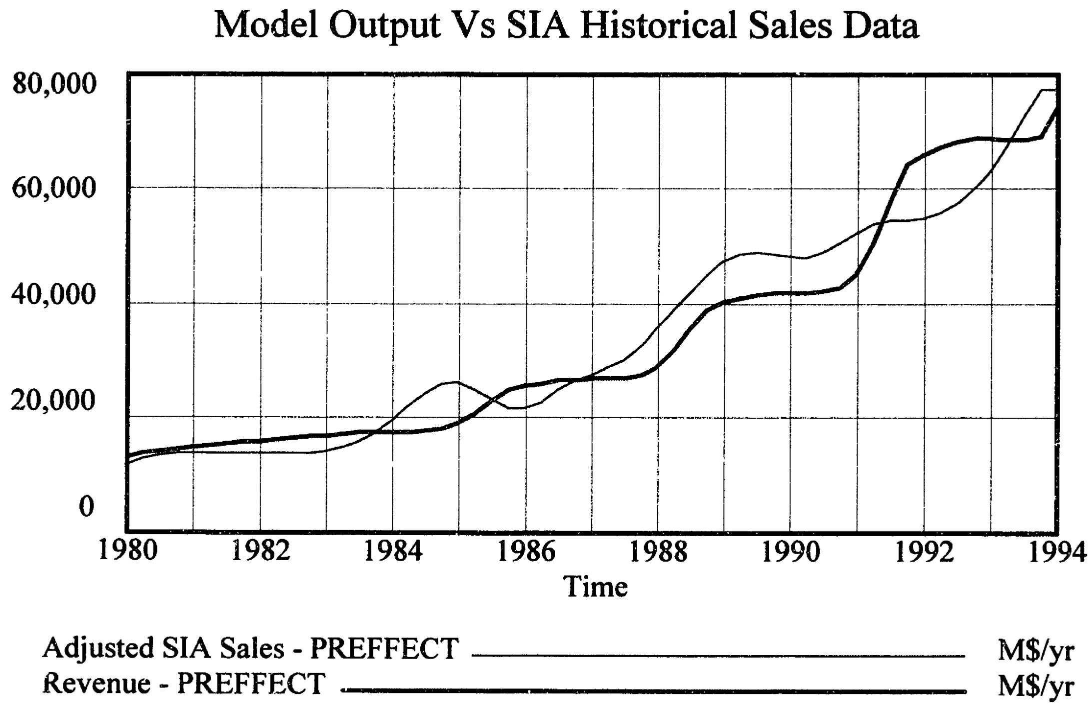

Figure 3.17 - Revenue Growth Resulting from Capacity Utilization Effects

## 3.4.2 Modeling Profitability and Industry Investment

One of the benefits of doing a retrospective model of the semiconductor industry is the benefit of hindsight. We know historically that the build up of semiconductor capacity in 1984 was in large part due to Japan, Inc. making a strategic investment in semiconductor capacity which resulted in a glut of DRAMS flooding the market in 1985. Clyde Prestowitz documents the dynamics of the DRAM crisis in his book Trading Places [Prestowitz 1988]. The over-capacity which existed in the 1984-85 time frame resulted in DRAM prices dropping below manufacturing cost. Most American companies exited the DRAM business, while the Japanese companies captured market share even though they suffered heavy losses estimated by Prestowitz to be over $4 billion. The rapid build-up of demand and revenues in 1984 and the decline in industry revenues in 1985 were due to the effects of Japan Inc.'s strategic investment in semiconductors.

One way of modeling this rapid buildup of capacity is to add the effects of profits on investment in the industry. Figure 3.18 shows the stock and flow diagram with the inclusion of margin

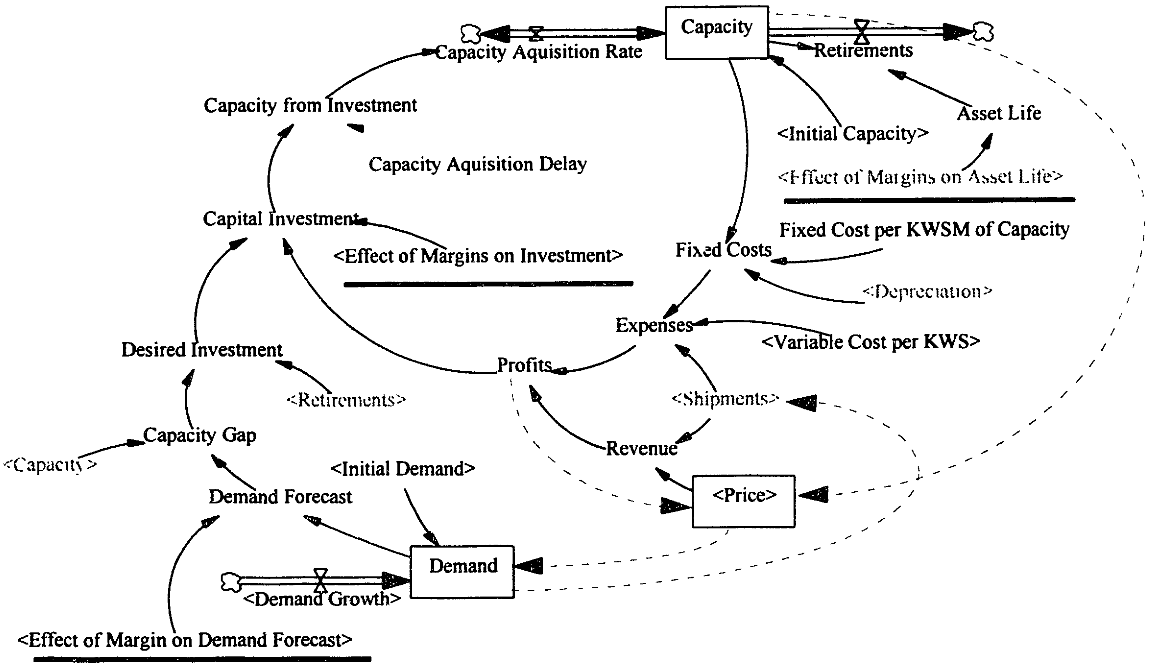

**Figure 3.18 - Stock and flow diagram with margin effects indicated**

effects which are underlined in the diagram for clarity.

Figure 3.19 shows the relationships between the three margin effects which are the Effect of Margins on Investment, the Effect of Margins on Demand Forecast, and the Effect of Margins on Asset Life. Margin corresponds to net margin or pre-tax operating margin since there are no interest or tax expenses in this version of the model. Margin is calculated by dividing Profits by

Revenue. The model assumes managers make decisions about Capital Investment based on Perceived Margins in the industry. If the Perceived Margins are good (i.e. Perceived Margin / Target Margin > 1), decision makers will inflate the Demand Forecast assuming that the industry will continue to grow more rapidly than the forecast would indicate. Good perceived margins will also attract new money to the industry as investors assume that they will be able to profit in the industry by taking market share from firms currently in the market. This was clearly the case with Japan in the mid 80s, and is the logic driving much of the Korean investment in semiconductors in the 90s [WSJ, March 15, 1995]. If margins are poor (i.e. Perceived Margin / Target Margin <1) Capital Investment and Demand Forecast will be deflated below what might be required to meet demand growth. In addition if margins are poor, Asset Life will be extended as older equipment is pressed into service in order to reduce the need for Capital Investment. If margins fall off sharply, Asset Life will be shortened as companies exit the business and write off their production equipment.

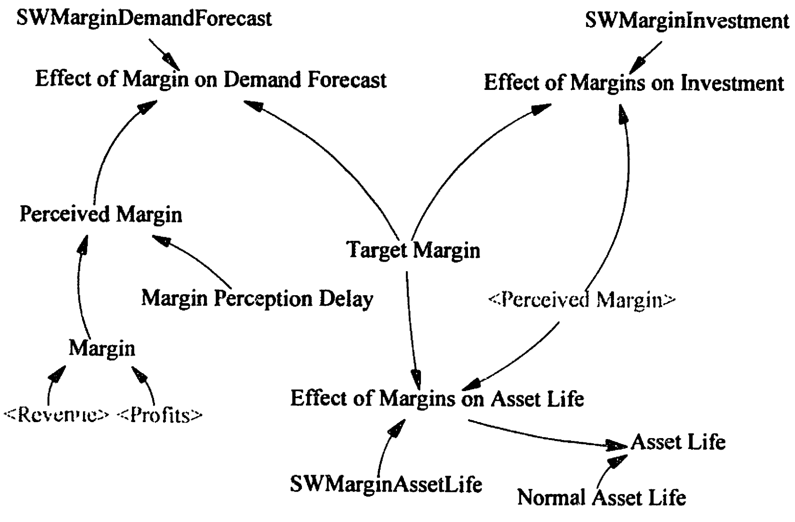

**Figure 3.19 - Calculating Margin Effects**

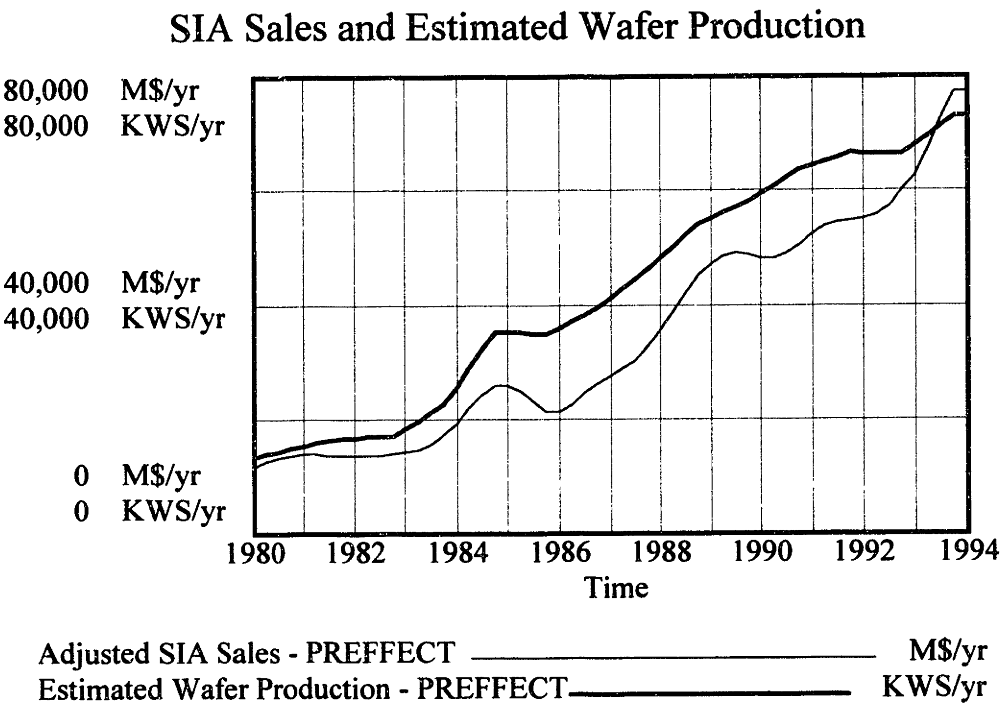

**Figure 3.20 - Estimated wafer volume Vs sales volume**

In order to apply the margin effects to the 1984-85 time period it is useful to get an estimate of the actual demand for semiconductor product during that time frame. The SIA tracks unit shipments as well as sales, and this information can be used to estimate the demand independent of prices. An estimate of wafer production can be obtained by assuming that the average area of a semiconductor product (discretes and ICs combined) has been relatively constant over the period of interest. Figure 3.20 shows the estimated wafer production along with the SIA Sales data. As can be seen in the figure, Estimated Wafer Production is relatively flat in 1985 and 1992 while the SIA Sales data shows a decline in sales volume due to price discounting.

Estimated Wafer Production will be used as a proxy for Demand in order to test the dynamics of margin and pricing effects together. In the model, Demand and Demand Forecast are measured in terms of wafer volume, not in terms of Price. In the model Price only effects Revenue. Orders, Shipments and Backlog are all measured in terms of wafer volume, not in terms of dollars.

Figures 3.21-3.23 show the output of the model when margin effects, price effects, and Backlog are turned on. The output of the model has been narrowed to the period 1980 through 1987 in order to concentrate on the rapid buildup of demand in 1984. As can be seen in Figure 3.21, the model shows that Demand builds up rapidly in 1984 due to price reductions which began in mid 1983 and lasted into early 1985. Figure 3.22 shows the corresponding model output of Revenue. Revenue declines in mid 1983, but then increases rapidly in 1984 as the Demand builds up.

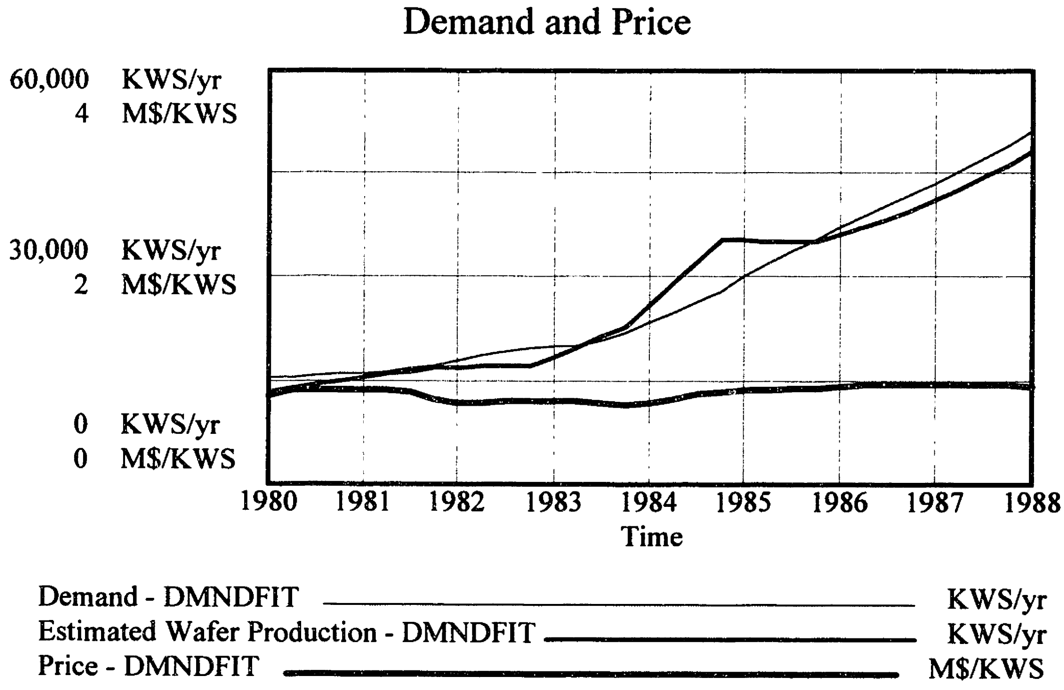

**Figure 3.21 - Demand growth due to price discounting and GDP multiplier effects combined.**

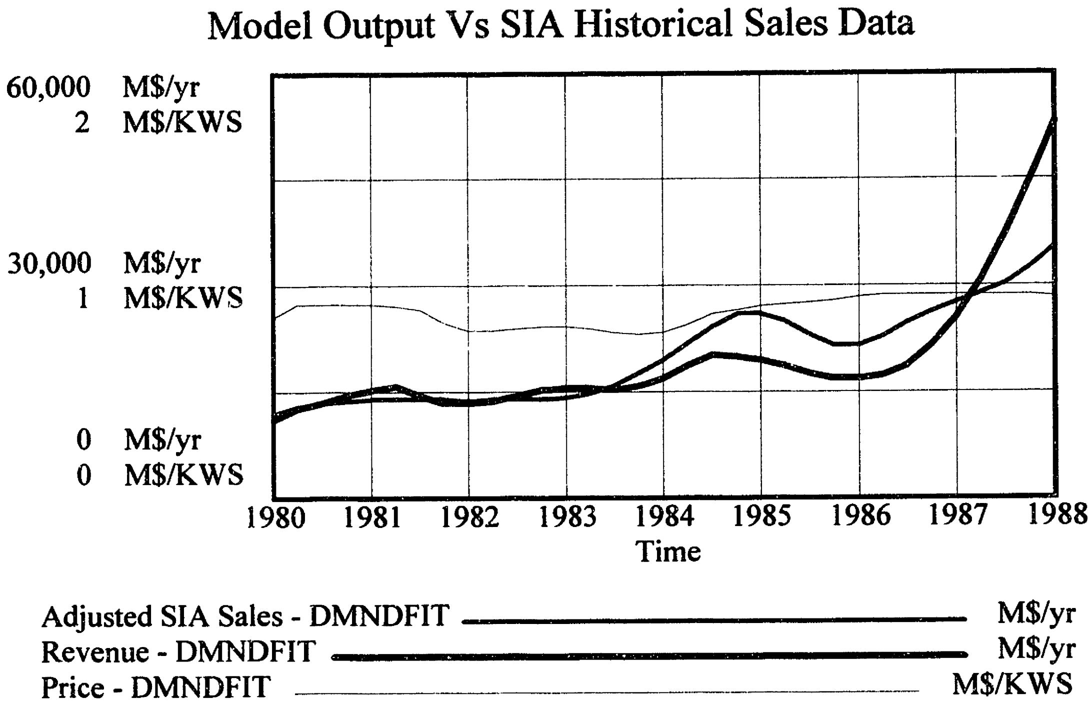

**Figure 3.22 - Revenue growth due to price discounting and GDP multiplier effects.**

Figure 3.23 shows the book to bill ratio generated by the model compared to the SIA historical reference. Although the model-generated Demand and Revenue match history reasonably well,

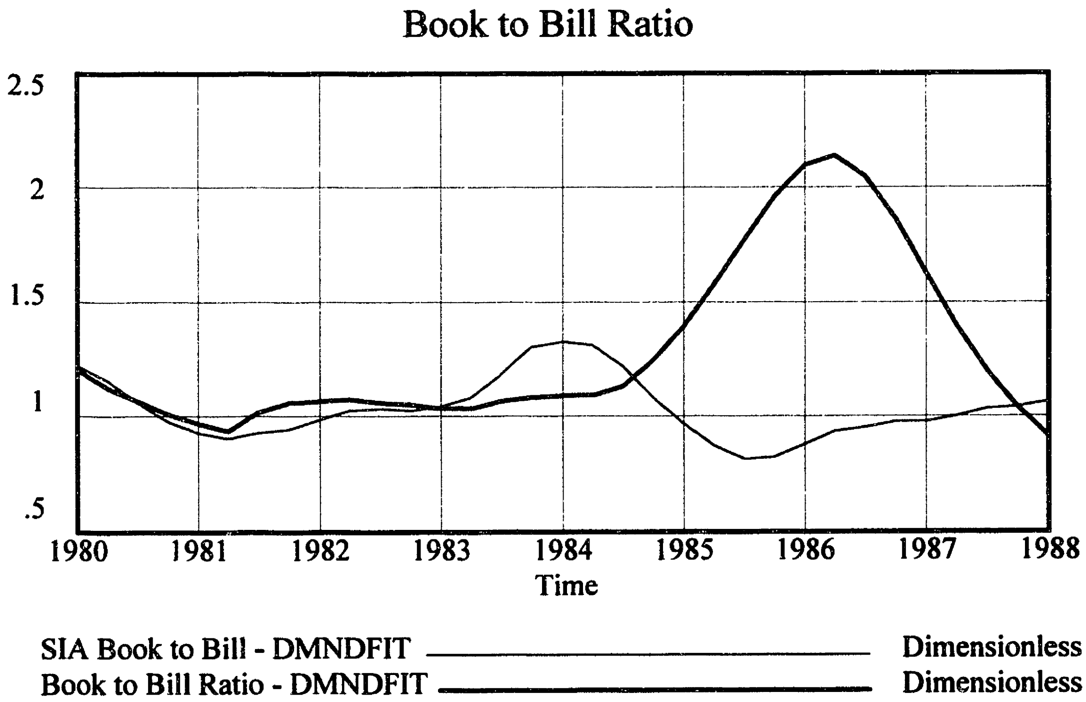

**Figure 3.23 - Book to Bill ratio with price discounting and GDP effects.**

the Book to Bill ratio is a poor match. This anomaly in the Book to Bill ratio requires closer attention because it points out a conceptual problem which will be discussed in the next section.

### 3.4.3 The Significance of Book to Bill Ratio

A book to bill ratio greater than one indicates that there is a shortage of capacity because Orders exceed Shipments which are limited by Capacity. Refer to the section on initializing Backlog for further explanation of the significance of the book to bill ratio. Historically, the book to bill ratio was greater than one all throughout 1983 and 1984 when the demand for semiconductors was increasing dramatically. This means that instead of excess capacity, which the model needs to produce growth, there was a shortage of capacity. Figure 3.24 shows the SIA Sales and Book to Bill data on the same graph. From the graph it is evident that the periods of most rapid growth in the semiconductor industry correspond to periods when the Book to Bill ratio was above one, and thus a shortage of capacity existed. This is inconsistent with the concept of rapid growth due to price discounting because of over-capacity.

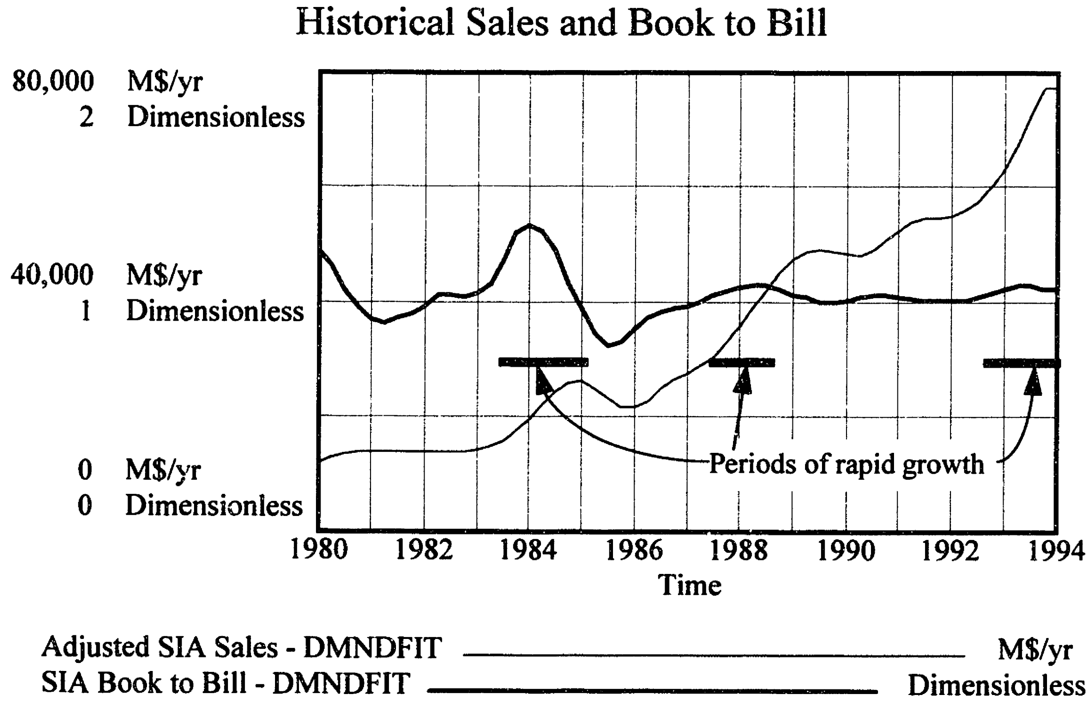

**Figure 3.24 - Periods of rapid growth in semiconductor revenues when Book to Bill greater than 1.**

### 3.4.4 Conclusions from Modeling Capacity Utilization Effects

Price discounting due to over-capacity does not adequately explain the historical buildup of sales and demand experienced by the semiconductor industry in 1984, because price discounting is inconsistent with a book to bill ratio which is greater than one. One would expect that if there were a shortage of capacity, manufacturers would be reluctant to drop prices unless there were a compelling reason to do so. One such reason could be that a new level of technology is available from competitors which has a much better price performance ratio than current technology. Customers may switch to the new technology early in its life cycle with the expectation that the prices will fall. This would cause the capacity utilization of the old technology to drop at the same time that the new technology was running a backlog. In order to explore such effects it is necessary to add a concept of technology progression to the model.

## *3.5 Modeling Technology Effects*

Investment in new manufacturing capacity is not the only investment that a firm must make. To stay in business in the long run, new products must be developed in order to replace obsolete products which consumers are no longer interested in purchasing. In the semiconductor industry new generations of products are enabled by new generations of technology which offer density and performance improvements over older technologies. Today we think nothing of purchasing a portable computer with 8 Megabytes of memory to run programs of low computational complexity such as word processing and spreadsheets. Twenty years ago, a machine with 8 Megabytes of main memory would have cost millions of dollars and required a room full of operators to keep it running. This progress has been brought to us through the continual improvement of semiconductor technology. Those improvements are generated through a high level of investment in research and development by firms involved in the industry.

The causal loop diagram of Figure 2.2 (reproduced below as Figure 3.25 for convenience) shows how R&D Spending leads to Increased Density and Performance, which leads to increases in both Demand and Prices. In the model, Demand is increased through changes in the Net Rate of Demand Growth, and Prices are changed through the Effect of Delivery Delay on Price and the Capacity Utilization Effect on Price. In order to add the effect of technology transitions into the model, a link must be made between technology capability and Demand (orders) for various technologies. Production must also be dis-aggregated into two or more technologies so that price differences between the technologies can be modeled.

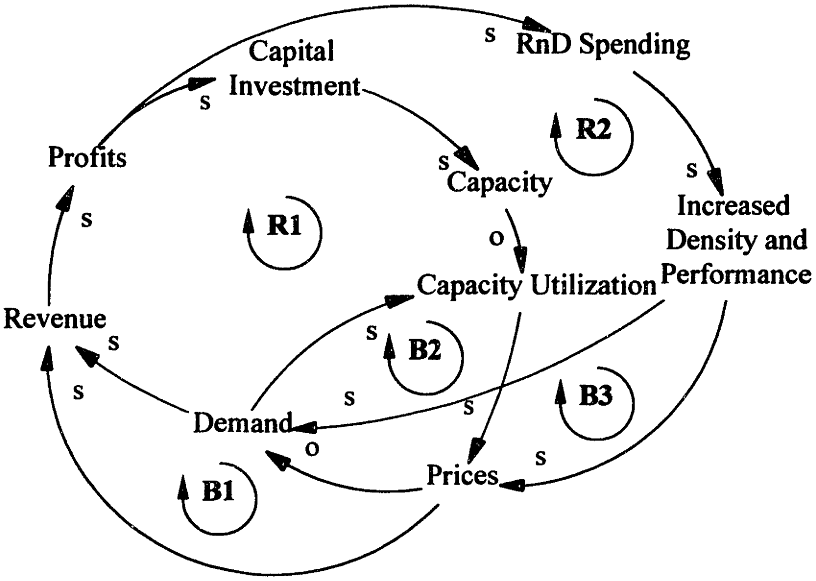

**Figure 3.25 - Causal Loop Diagram for Technology Effects.**

There have been five technology transitions between the years 1980 and 1994. In 1980, 64Kbit DRAMs had just been introduced, followed in 1983 by 256Kbit DRAMs and in mid 1986 by 1Mbit parts. 1989 saw the introduction of 4Mbit parts, followed by 16Mbit DRAMs in 1992. At the end of the simulation period, 64Mbit DRAM parts were just becoming available. This represents a 1000 fold increase in the number of DRAM bits which could be fit into a single package over a 15 year period. In order to keep the model from becoming overly complex, only one technology transition will be modeled, in the 1983-84 time frame. That is the period which corresponded to the build-up in demand prior to the DRAM crisis of 1985, a time in which Japanese manufacturers were investing heavily in manufacturing capacity for 256K DRAMs.

### 3.5.1 R&D and Technology Performance

The density and performance of semiconductor processes is built up through ongoing R&D into new manufacturing procedures. As one technology matures, the rate of improvement in the process resulting from an incremental dollar invested in R&D for that process begins to slow down. R&D may be proceeding on several generations of semiconductor process at a given time. As the incremental improvements available in one technology begin to decline, R&D investments are switched to newer technologies. In order to model this effect without getting side tracked by the details involved in R&D, exogenous table functions are used to determine a Density / Performance index for each technology as a function of R&D spending on that technology. Only one technology transition is modeled, but the addition of other technologies would be straightforward.

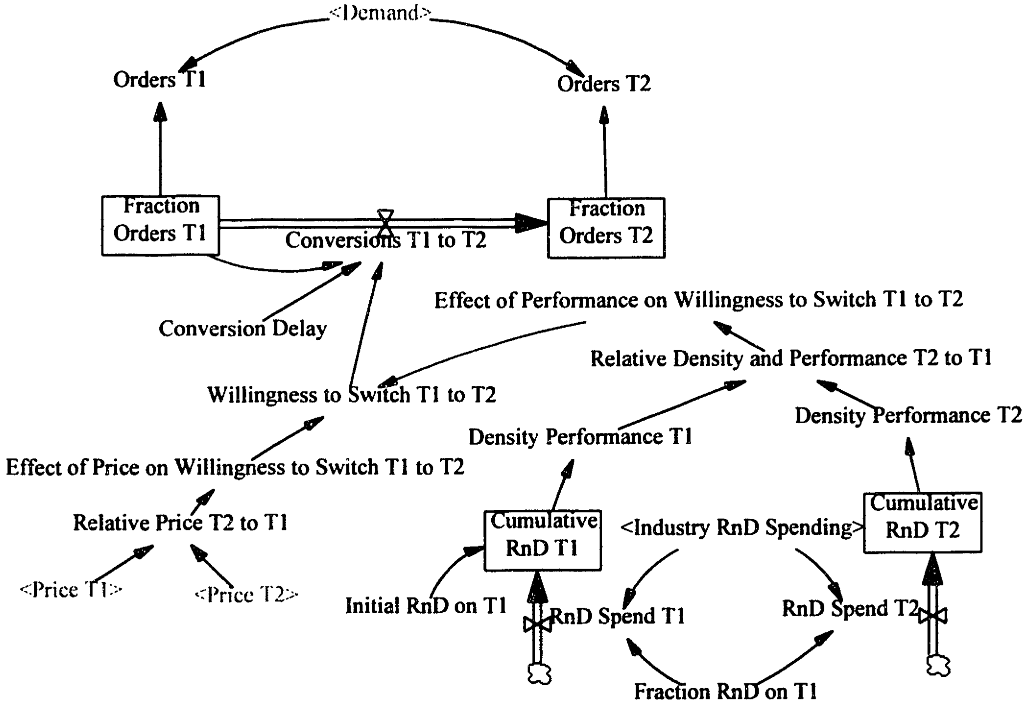

**Figure 3.26 - Stock and Flow Diagram for Technology Effects**

### 3.5.2 Modeling Technology Transitions

Figure 3.26 shows the stock and flow diagram used for modeling technology transitions. The Demand for semiconductors is split into orders for technology T1 and orders for T2. It is assumed that the fraction of orders for T1 starts out at one, and gradually drops to zero as customers convert over to using the newer technology. The conversion process is determined by the flow Conversions T1 to T2, whose value is determined by the Willingness to Switch T1 to T2. The willingness to switch technologies is determined by the relative price and the relative density and performance of the two technologies. The density and performance of each technology is determined from the cumulative R&D invested in each technology.

The Industry R&D Spending is divided between the two technologies by the Fraction R&D on T1 variable which starts out at one, and drops to zero over a year and a half period beginning in mid 1980. This models the transition of R&D spending from 64K DRAM technology, which was introduced in 1980, to 256K DRAM technology, which was introduced in 1983. The model output in Figure 3.27 shows the resulting Density Performance index for T1 and T2, and the resulting Willingness to Switch T1 to T2.

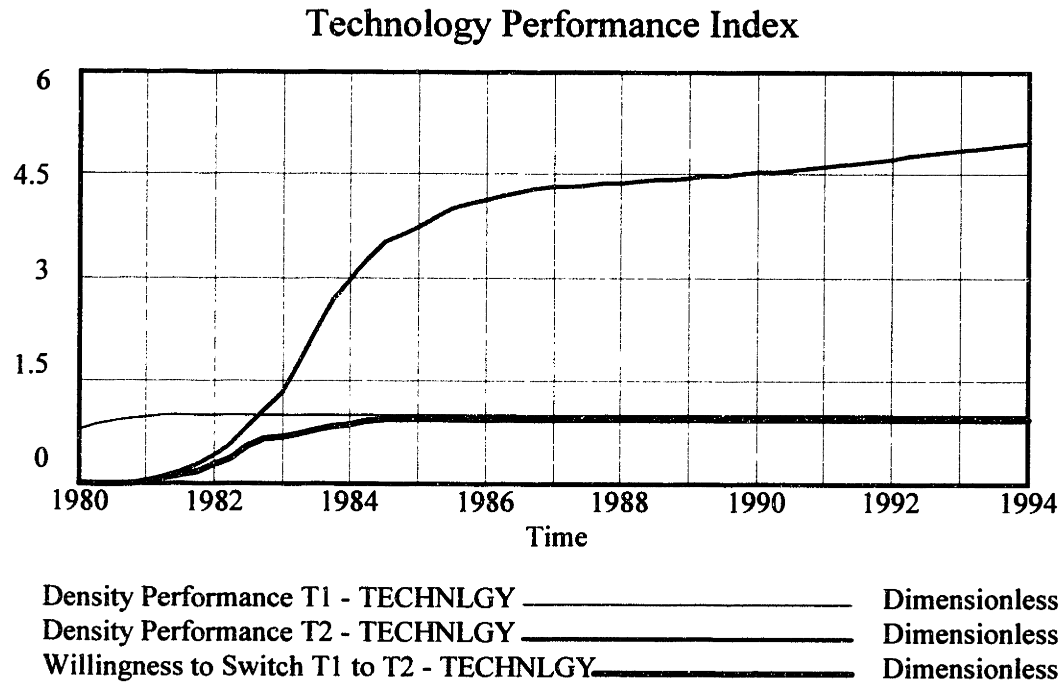

**Figure 3.27 - Density \ Performance and Willingness to Switch Technologies**

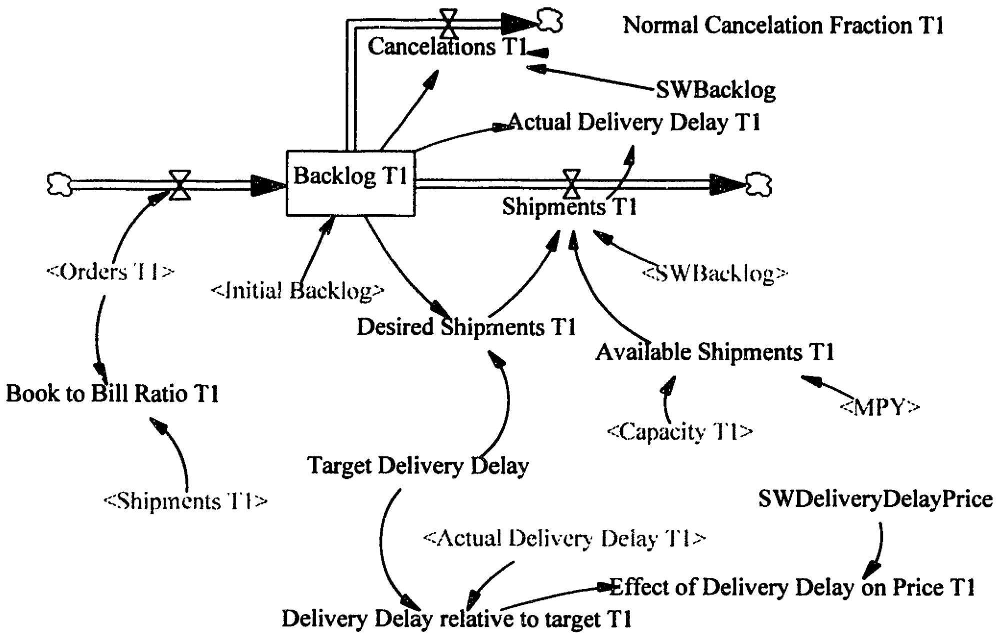

**Figure 3.29 - Stock and Flow Diagram for Distribution of T1**

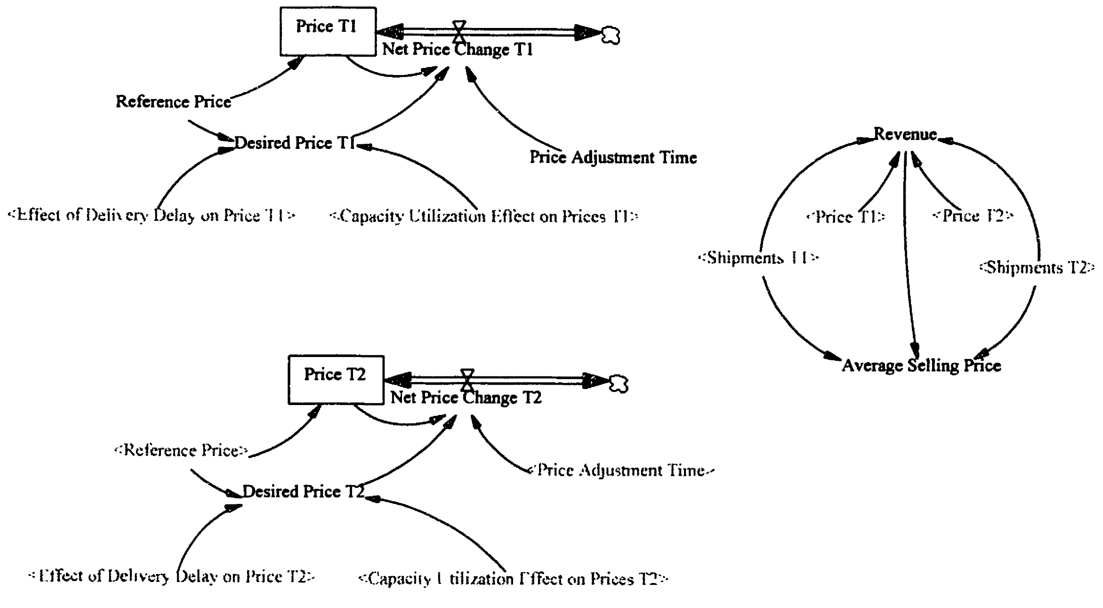

**Figure 3.28 - Price and Revenue Calculations for Multiple Technologies**

Each technology has its own Distribution sector which tracks capacity, shipments, backlog and delivery delay for that technology. Figure 3.29 shows the stock and flow diagram for Backlog and Shipments for technology T1. The stock and flow diagram for T2 is identical to that for T1 with the exception that the Initial Backlog for T2 is assumed to be zero since the technology was not available at the beginning of the simulation. The pricing calculation for each technology is identical to the one used in modeling capacity utilization.

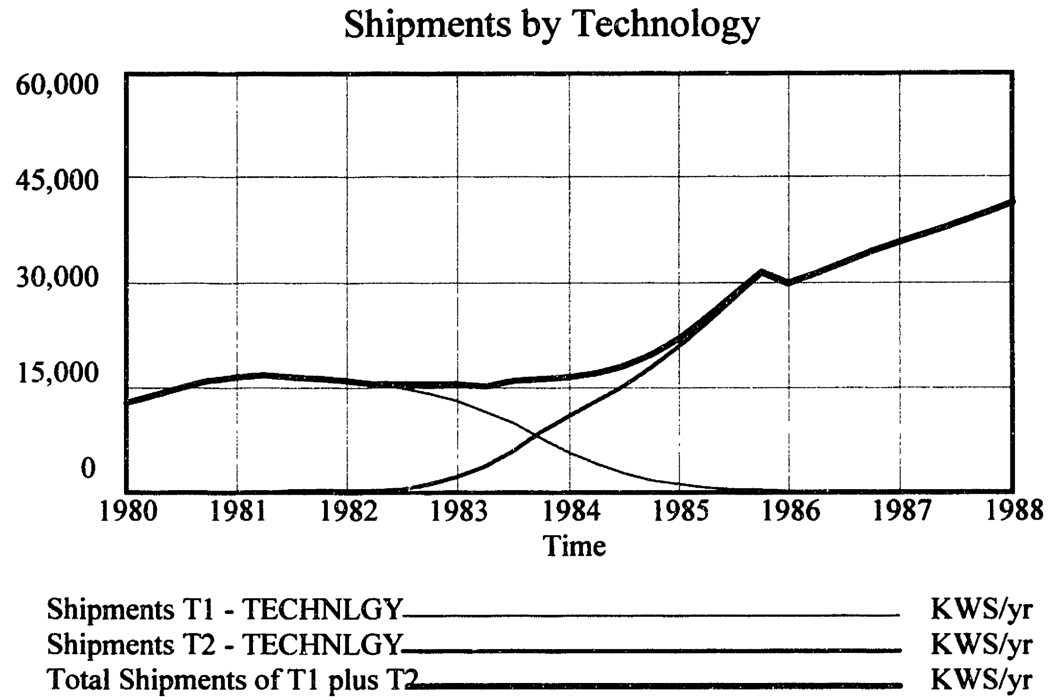

**Figure 3.30 - Model Output of Shipments by Technology**

Figure 3.28 shows the stock and flow diagrams for determining Price of T1 and T2, along with the calculation of Revenue and Average Selling Price. Revenue is the sum of the Price times Shipments for each technology, and the Average Selling Price is the total Revenue divided my the total Shipments.

Figure 3.30 shows the model output of the shipments for each technology along with the total shipments of all technologies between 1980 and 1988. As can be seen from the figure, shipments for technology T2 start out at zero, and transition to 100% of the total shipments over a four year period beginning in 1982.

The manufacturing capacity is assumed to be entirely dedicated to technology T1 at the beginning of the simulation, and is converted entirely to technology T2 by simulated time 1986. This conversion is handled by the stock and flow diagram shown in Figure 3.31. Capacity conversion is driven by a Willingness to Convert Capacity T1 to T2 that is a function of the fraction of orders for technology T2 and the relative density and performance of the technologies. The policy implied by Figure 3.31 is that managers will begin to convert capacity to the new technology in anticipation of customer orders. If orders for the new technology exceed expectations, the conversion process will be accelerated, and if orders lag behind expectations, the conversion will be delayed.

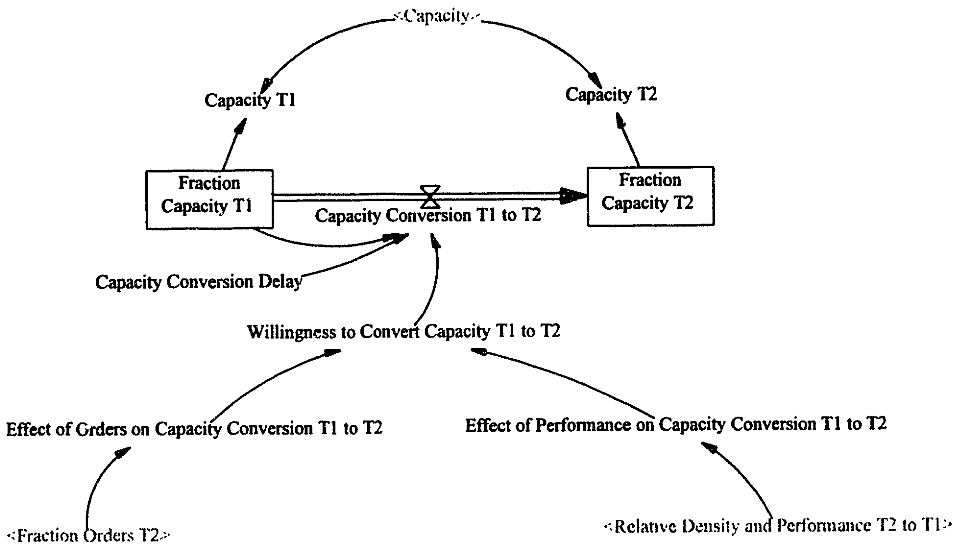

**Figure 3.31 - Stock and Flow Diagram for Capacity Conversion between Technologies**

### 3.5.3 Demand Growth from Technology Improvement

Demand growth is determined endogenously by summing together all of the factors which effect growth. The calculation of the Net Rate of Demand Growth is shown in Figure 3.32. All of the

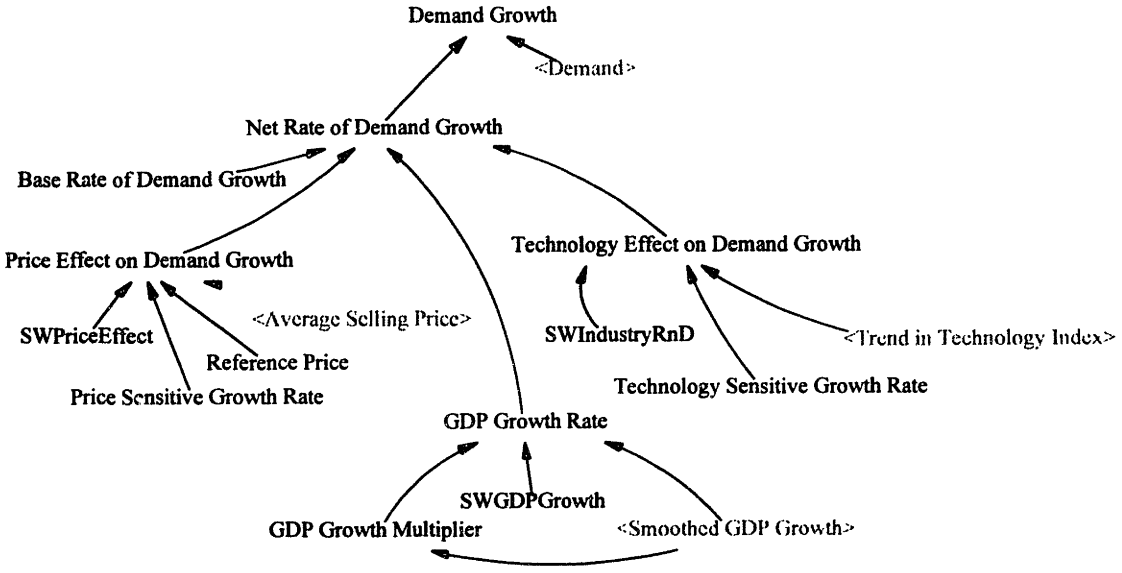

**Figure 3.32 - Calculation of Demand Growth with Technology Effects**

model output that follows results from running the model with all of the effects shown in Figure 3.32 turned on. The GDP Growth Rate and Price Effect on Demand Growth have been discussed in earlier parts of this chapter.

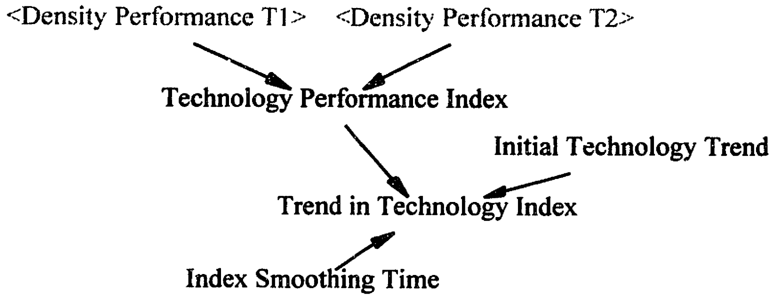

Figure 3.33 - Calculation of Trend in Technology Index

The Technology Effect on Demand Growth is determined from the Trend in Technology Index which is calculated using Vensim's TREND function as shown in Figure 3.33. The trend function is used to track the rate of change of the composite Technology Performance Index, which is the maximum of Density Performance T1 and Density Performance T2 at any point in time. As R&D spending on technology T2 increases, its performance index rises above that of T1 and the

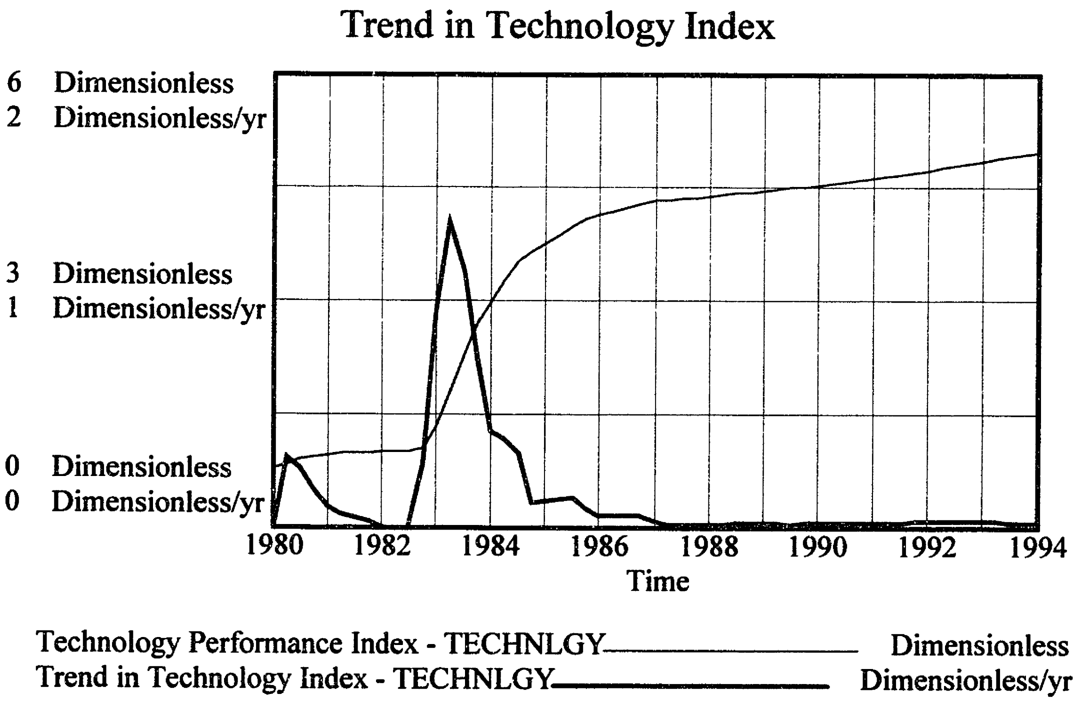

Figure 3.34 - Model Output of Trend in Technology Index

composite Technology Performance Index begins to increase rapidly. The resulting trend function is shown in Figure 3.34. The trend increase in 1982-84 drives an increase in demand during that period.

In addition to the technology effects which are explicitly modeled by the stocks and flows shown in this section, the Price Effect on Demand Growth has been adjusted to more accurately reflect the short-run price elasticity of demand for new semiconductor products.

Figures 3.35-3.37 show the model output when the technology effect is added to the effects of GDP growth and the effects of capacity utilization. These figures are analogous to Figures 3.21-3.23 in the section on modeling profitability and industry investment.

A close comparison of Figures 3.21 and 3.35 shows that the model generated demand tracks the exogenous variable Estimated Wafer Production reasonable well in both figures. Price in Figure 3.21 is reduced in the 1982-84 time period, while Figure 3.36 shows no significant price reduction until 1986 which more accurately reflects the historical record for average selling price

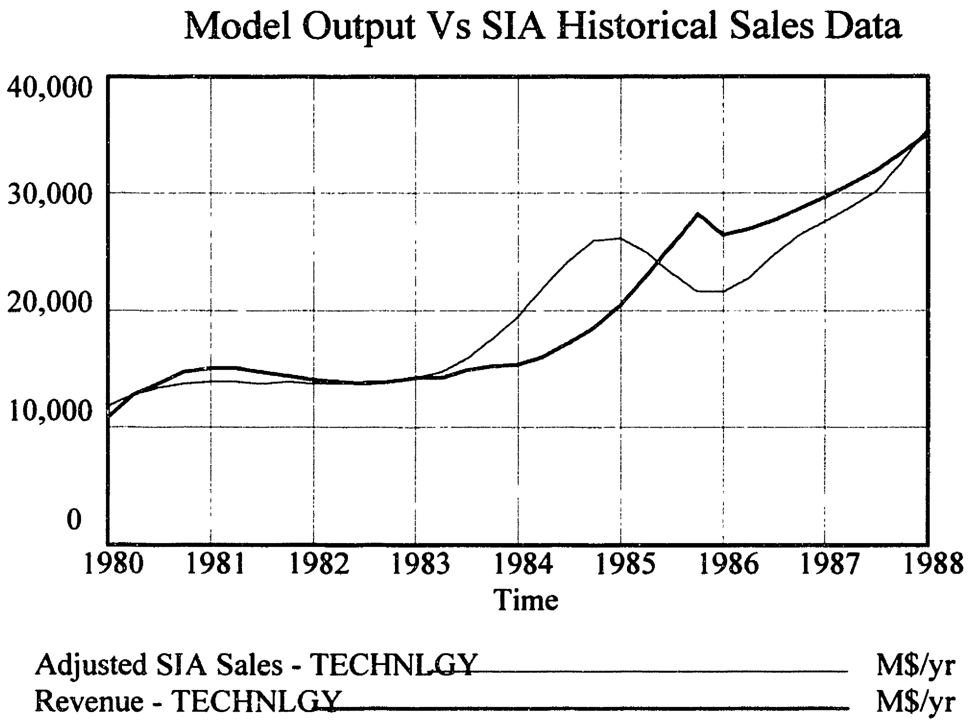

**Figure 3.35 - Revenue with Technology Effects**

of semiconductors shown in Figure 3.4 - Average Selling Price of Semiconductors.

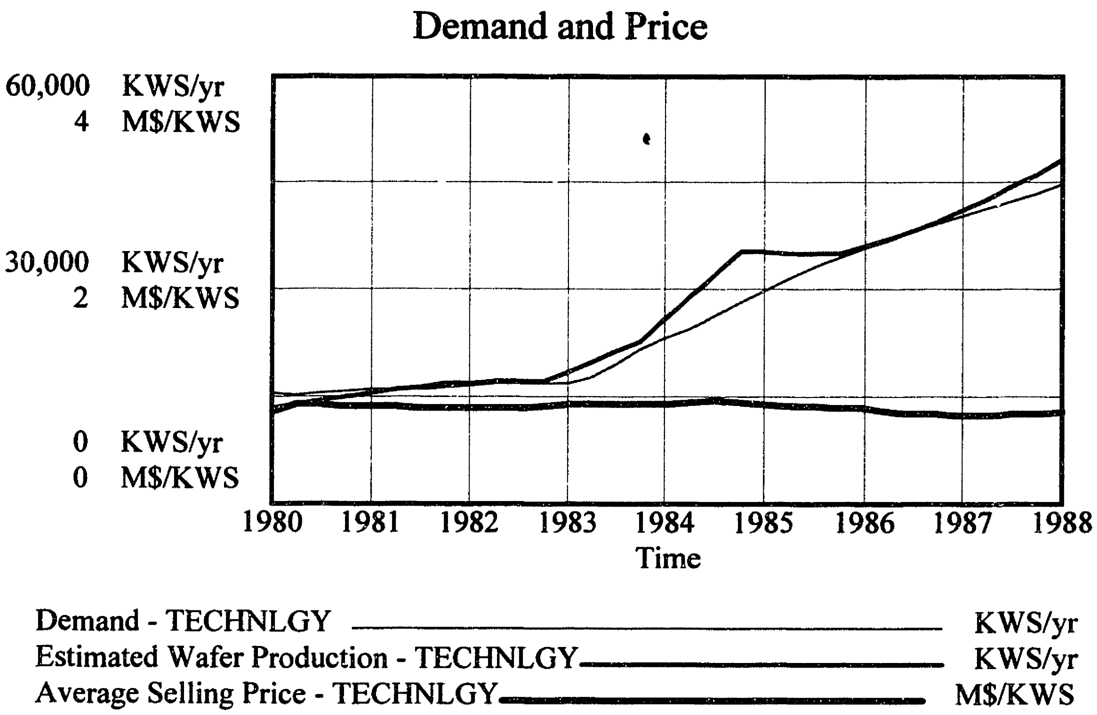

**Figure 3.36 - Demand and Average Selling Price with Technology Effects**

The Revenue shown in Figure 3.35 more accurately represents the rate of growth in 1984-85 and 1987-88 than does the corresponding model output in Figure 3.22.

The most significant improvement in the model output resulting from the addition of technology effects occurs in the match with the Book to Bill Ratio shown in Figure 3.37. The model generated Book to Bill ratio tracks the historical record almost exactly until 1984 after which time it tracks the general trend in Book to Bill much more accurately than the output shown in Figure 3.23. Overall, the technology effects combined with the GDP effects explain most of the variations in growth which occurred during the early 1980s.

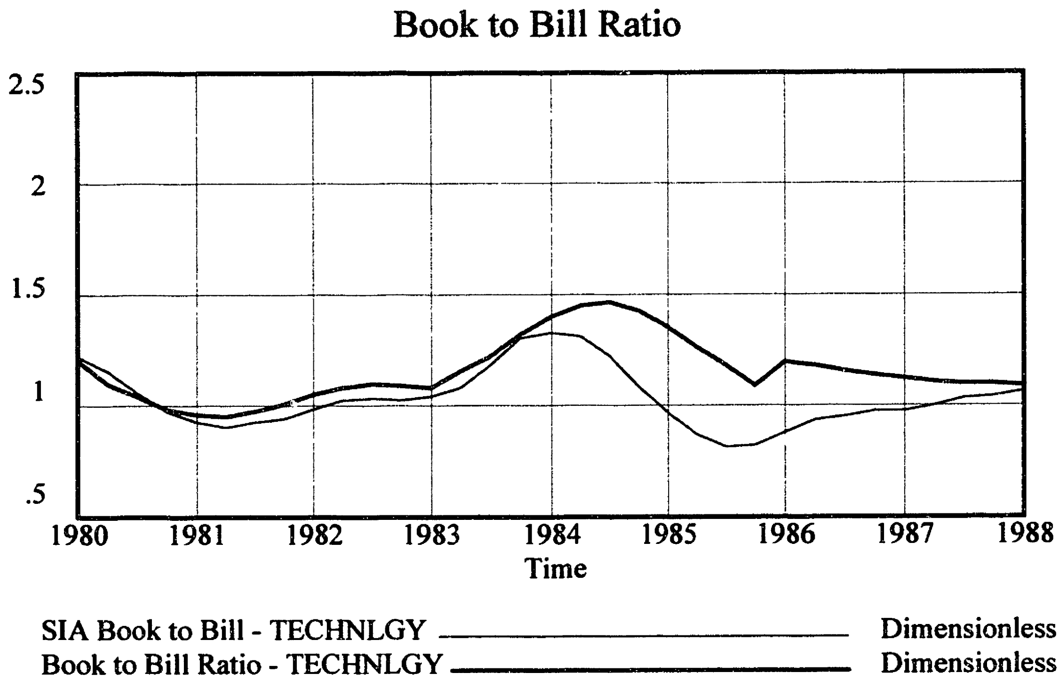

**Figure 3.37 - Book to Bill with Technology Effects**

### 3.5.4 Conclusions from Modeling Technology Effects

The main conclusion to be drawn from this thesis is that GDP and technology effects play a much larger role in determining the patterns of demand growth in the semiconductor industry than do price reductions driven by excess capacity. Referring back to Figure 3.24, there were three periods of rapid growth which corresponded to times when the Book to Bill ratio was greater than one for extended periods. The hypothesis that these periods result from increased demand for semiconductors resulting from a technology transition is given credence by the match obtained to historic data in the 1980-88 time frame after the addition of a technology transition in that time period. The technology performance index improves only slightly in the model after 1987, therefore one would expect that the model would not predict either the rapid build-up in demand in the 1988-89 time frame or the current build-up which started in mid 1992. Examining the model output over the entire time period shows that without technology advancement beyond 1987, the model predicts that there would be much larger fluctuations in revenue due to the effects of price reductions stemming from commoditization in the semiconductor industry. The bottom line conclusion is that if the rate of technological advancement in the semiconductor industry ever slows down, the fluctuations in capacity utilization and price will become significantly more pronounced than they are today.

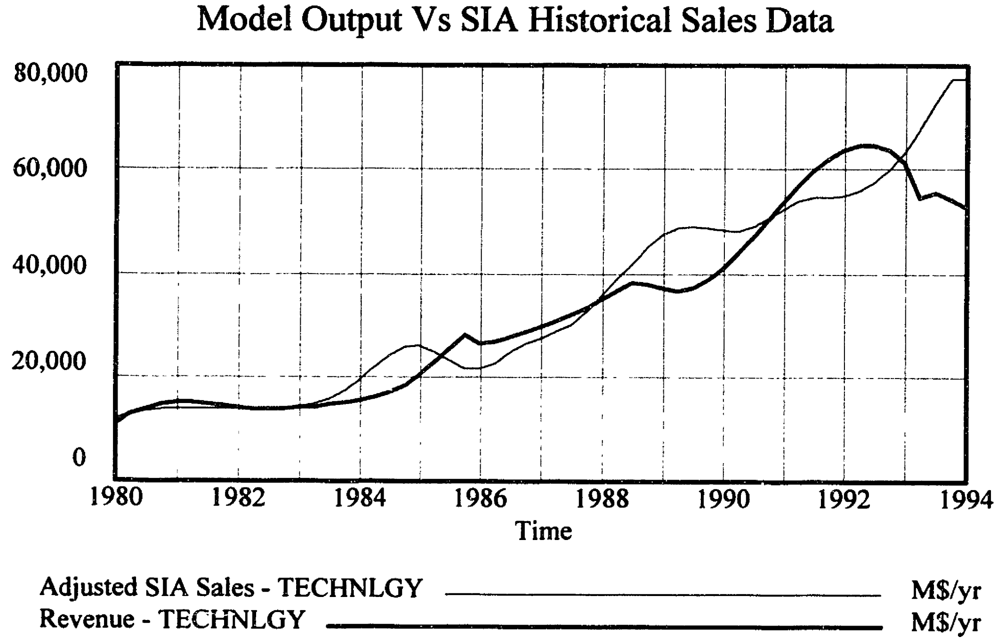

**Figure 3.38 -Increased Revenue Fluctuations without Technology Improvements**

# 4. Model Evaluation and Future Work

## *4.1 Accuracy Vs Adequacy*

The purpose of building a model is to create a representation of some real-world phenomena from which significant insights can be gained. Any model is less complex than the phenomena itself. The accuracy of any model is determined by two main factors. The first factor is the extent to which the model structure represents the actual policies and decision structures which are in place in the real world. The second factor is the data used to drive the model both through exogenous inputs and policy decisions implied by table functions. No model can provide accurate predictions of phenomena which are not modeled. Even the most accurately constructed models cannot provide accurate output if the input data is flawed.

The adequacy of any model depends on the purpose for which it is intended. A model that matches historic data within a factor of two may be more than adequate as a learning aid by which significant insights into a problem can be obtained. A model that matches historic data within 20% may give enough confidence in its structural accuracy to be used as an aid in making policy decisions for a firm. A model that consistently matches real world data within 5% could provide guidance for investment decisions.

### 4.1.1 Adequacy for Learning

My purpose in writing this thesis was two fold. I wanted to learn more thoroughly how system dynamics could be applied to a real world problem, and I wanted to learn more about the driving forces behind the business cycles in the semiconductor industry. From the learning perspective, the model developed in this thesis has been extremely useful. A formal model allows testing of various hypotheses against real-world data. One of my hypotheses when I started this thesis effort was that a lack of capital investment during the recession caused by the Gulf War in 1990-91 was a key determinant of the shortage of semiconductor capacity which has existed since 1992. From my model I have learned that this may well be the case, and that managers dare not ignore the fact that demand for semiconductors is significantly more volatile than GDP.

There is much more that could be learned from the model as it now stands, and some simple extensions to the model could expand its learning potential significantly. This will be discussed in the next section.

### 4.1.2 Adequacy for Policy Decisions

Imbedded in this model are a number of policies which underlie real world decisions which managers in the semiconductor industry must make on a daily basis. The pricing policies which are built into the capacity utilization effects model how managers deal with under and over capacity in their manufacturing facilities. The capital investment and industry R&D policies inherent in the model reflect major strategic decisions which top management must make on a periodic basis. However, the model simulates the effect of these policies in aggregate, and does not model the response of an individual manager in a particular firm. Use of the current model to explore policy variations would answer such questions as: What would be the effect on industry revenues if the managers in the semiconductor industry chose to delay investments in capital equipment because they perceived that the potential for return on investment was small? or Would industry revenues rise or fall if managers were more aggressive about lowering prices during times of industry over-capacity?.

The current model cannot be used to answer questions about the profits of an individual firm, since the policies built into the model apply to the industry as a whole. The model could be extended to allow policy differences between segments of the industry. This direction of research is discussed under the section entitled Further Work.

### 4.1.3 Inadequacy for Forecasting

The current model is inadequate for forecasting for several reasons. First and foremost, although the technology effects have provided a much-improved match with historic data in the 1980-88 time frame, only one technology transition has been modeled. The analysis in Chapter 3 indicated that at least three technology transitions are needed to accurately represent the semiconductor industry through 1994. In addition, to use the model for forecasting into the future, a model of the dynamics of technology transitions would be required. The model currently treats the changeover in R&D investment from one technology to another as an exogenous event. The dynamics for technology progression would have to be handled endogenously if the model were to answer such questions as: will the increasing cost of new fabrication facilities delay the introduction of new technologies.

A second reason that the model is inadequate for forecasting is that it doesn't match historic data closely enough to give confidence that all of the major influences effecting the industry are represented. In particular, the model's predictions of the market collapse in 1986 fall short of the magnitude of the collapse which actually occurred. Extensions of the model to handle "strategic" investments which are made based on expectations of future returns that are not supported by current profit margins or extensions to handle "phantom orders" by customers which disappear when industry backlog disappears could improve the fit with historic data.

## *4.2 Further Work*

As with any modeling effort, the act of creating a model leaves one with many ideas as to what else might be done. The modeling philosophy which my advisor has advocated (and I have adopted) is to add structure to the model only when necessary to answer a particular question. There are many questions left to answer about the determinants of growth patterns in the semiconductor industry. I will touch on a few of them, and leave their answers as an exercise for the reader, or the author at a later date. Any one of the improvements listed below could easily double the complexity of the model. All of them taken together would cause a geometric explosion in complexity. It is important to understand what kind of questions are of interest to the users of the model in order to guide future development.

### 4.2.1 Additional Technology Transitions

There have been five major technology transitions during the years between 1980 and 1994. Only one of these transitions has been modeled. There is much data on the price and volume of DRAM products over this period. New DRAM products are introduced every two and a half to three years at an initial price which increases with each generation. Prices within a DRAM generation fall quickly as manufacturers move down the learning curve and competitors enter the market. Within five years of the introduction of a new generation of technology, DRAM prices have fallen by an order of magnitude. Clearly there is more variation within a technology generation than the average selling price numbers reported by the SIA would indicate. In order to accurately model the intra-generational price movements, the model would have to be extended to include more structure in the technology pricing sector.

The role that capital equipment capability plays in improving semiconductor productivity is another technology effect that could be modeled. SEMATECH has estimated that the manufacturing costs of semiconductors has dropped by 25-30% per year while the feature size has decreased by only 12%-14% per year. The rest of the improvement has come from increases in wafer size, yield improvements and increases in the productivity of other manufacturing equipment. According to SEMATECH forecasts, the effects of increasing wafer size and yield improvement are diminishing, and the only way that the industry will maintain its reduction in manufacturing costs is to improve the productivity of manufacturing equipment by 9%-15% per year. Those kind of productivity improvements will undoubtedly increase the cost of capital equipment dramatically. At least one author [Maly 94] has predicted that the increasing cost of semiconductor processing equipment will cause the cost per function to increase with the introduction of new technologies rather than decrease as it has done historically. Even Gordon Moore (of Moore's Law, which states that the number of transistors which can be integrated onto a single chip doubles every 18 months) has said that no law lasts forever, and that the pace of change will slow down in the near future. Clearly a model of equipment cost and productivity would be a necessary addition to the model if one wished to use it for long term forecasting.

### 4.2.2 More Extensive Financial Sector

In the current model of the global semiconductor industry, firms are allowed to invest whatever amount is necessary to add the capacity needed. All funding is assumed to come from equity issues, and there is no explicit accounting of interest or tax expenses. Clearly, these expenses are important variables in making capital investment decisions. Many US semiconductor manufactures are locating plants overseas or moving plants to states which offer tax and / or

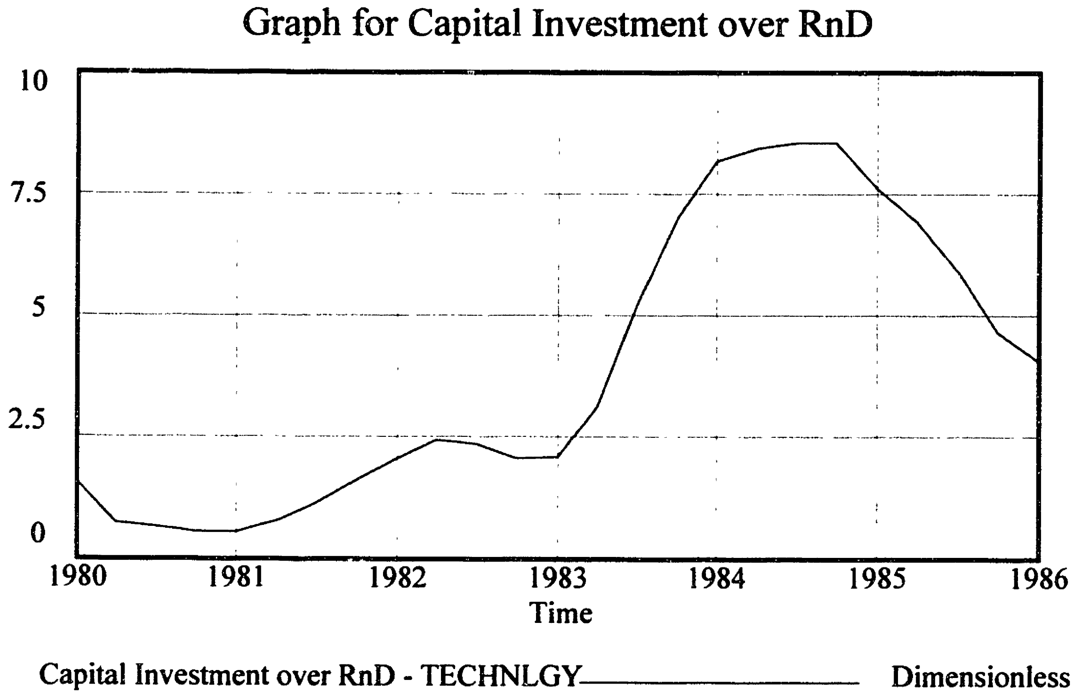

Figure 4.1 - Ratio of Capital Investment to R&D Expense

investment incentives. A more accurate accounting of cumulative profits and losses within the model could help highlight the reasons for these investment decisions. Figures 4.1 and 4.2 show some simple financial ratios computed by the model which raise interesting questions about the industry. Figure 4.1 shows the ratio of capital investment to total R&D spending. During the early 1980s the model shows that the industry was spending significantly less on capital investment than they were on R&D. By 1984, the industry was spending over seven times more on capital equipment than they were on R&D. Similarly, Figure 4.2 shows that in the early part of the 80s, revenue exceeded the sum of investments and R&D spending by more than a factor of 5 while in 1984 revenues barely covered the combined cost of R&D and capital equipment. The fluctuations in these ratios are undoubtedly exaggerated by the problems discussed in the next section, but the phase relationship between the cycles in these figures suggests that more aggressive investments in R&D during the early part of a technology cycle could lead to reduced

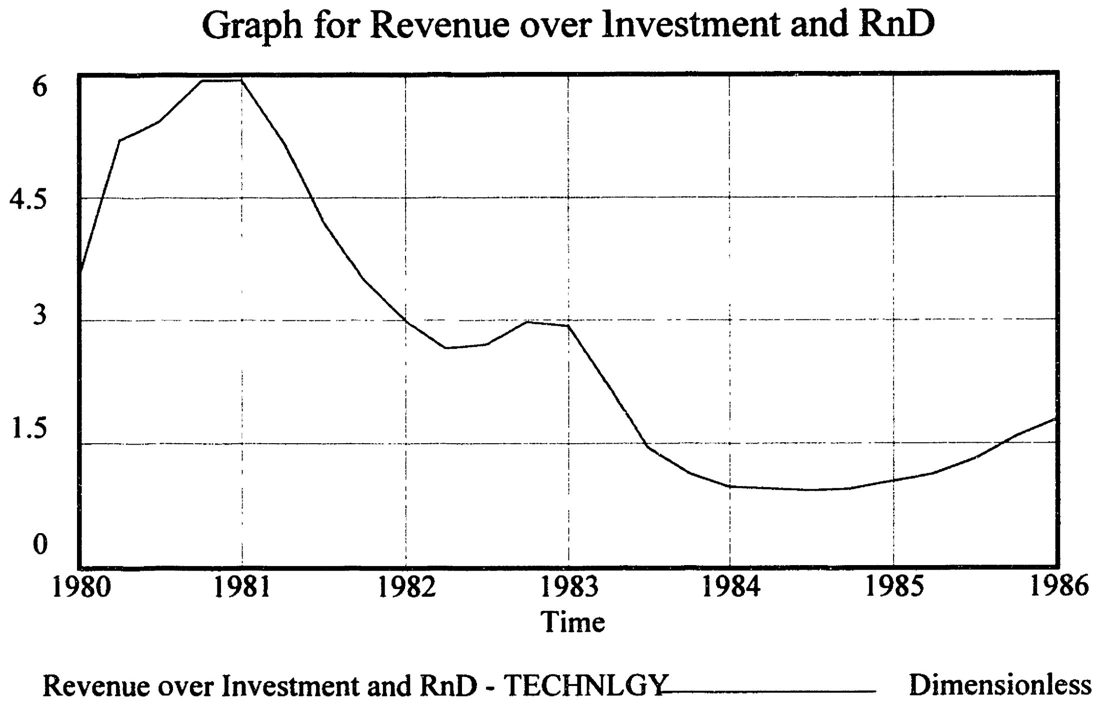

**Figure 4.2 - Ratio of Revenue to Capital Investment and R&D**

levels of capital investment later in the cycle. This could help to damp the cycles in profitability experienced by the industry.

### 4.2.3 Improved Handling of Capital Investments

The SIA doesn't track worldwide capital investments for the computer industry, but it does track investments in R&D and capital equipment for US merchant semiconductor firms. This data shows a steep rise in investments in 1984, followed by a decline in 1985 and 86. Since 1986 the investment by US merchant suppliers has grown relatively steadily at about 13 percent per year, and has not been subject to the fluctuations associated with "silicon cycles." The model output shown in Figure 4.3 shows a cyclic pattern in Capital Investment which begins with the buildup in 1984 and repeats with a period of approximately five years. This cycle is persistent with changes in the model, and exists to a lesser degree when the only effect active is the effect of the GDP multiplier (labeled Capital Investment - BASE in Figure 4.3). This oscillation is coming in part from the formulation of the demand forecast which extrapolates demand growth based on past growth rates smoothed over a forecast smoothing time. Extending the forecast smoothing time to 10 years (labeled Capital Investment - FCST10YR in Figure 4.3) reduces the magnitude of the cycles, but it still differs significantly from the SIA data. Alternate methods of forecasting Demand which work better in situations involving exponential growth should be explored as a means to bring the model generated investments more in line with the SIA data.

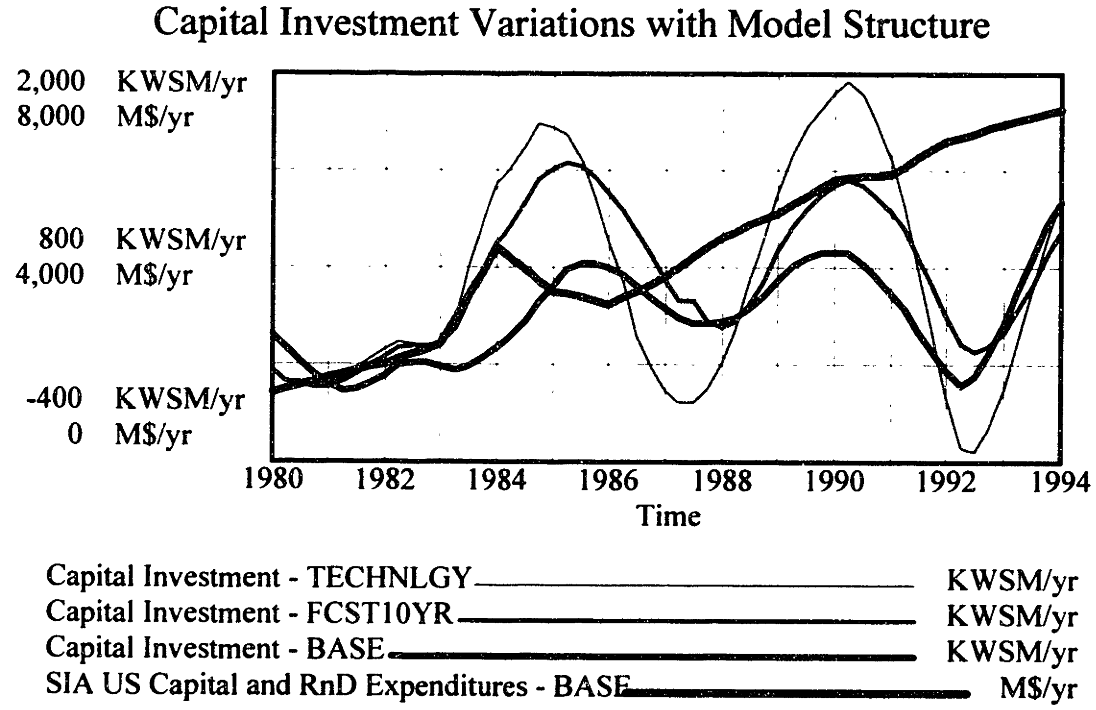
Capital Investment Variations with Model Structure

**Figure 4.3 - Model Generated Cycles in Capital Investment**

Of course an alternate possibility is that the investment in semiconductor capital equipment really does display the cycles exhibited by the model, but the additional investments are being made by other than US based merchant manufacturers. Certainly the investments made by Japanese and Korean semiconductor suppliers would not show up in the SIA data. To distinguish between these two possibilities, data on worldwide investments in semiconductor equipment needs to be obtained.

### 4.2.4 Explicit Models for Consumer Demand

Demand Growth in the model is calculated through the use of a combination of endogenous and exogenous variables. Growth driven by the GDP multiplier is exogenous, while growth generated by both technology effects and price reductions due to over-capacity are endogenous. Consumers' willingness to buy electronic products is not only effected by GDP growth variations, but it is also effected by technology capability. Consumer's willingness to replace an existing computer with a new one will depend on how much more functionality the new machine has compared to the one it is replacing. If the incremental functionality is not large enough, the computer purchase may be put off until the next generation of technology arrives.

Consumer demand has only an indirect effect on semiconductor sales because the purchasers of semiconductor products are not the end consumer but manufacturers who use the semiconductors to produce consumable goods. However, the cost and performance of semiconductors influence the designs of new products. If electronic product designers believe that they can lower their overall manufacturing costs by replacing two chips in an old technology with a single chip in a newer technology, they will switch their new designs to use the newer technology. A more explicit model of the dynamics of electronic product life-cycles and their effect on semiconductor buying patterns could improve the accuracy of the model as a forecasting tool. This could be especially useful for semiconductor suppliers who have a close relationship with their end customers. A collaborative venture between semiconductor manufacturers and electronic product manufacturers to model end consumer demand could help to eliminate the fluctuations resulting from amplification of errors along the technology supply chain.

### 4.2.5 Modeling the Semiconductor Technology Supply Chain

The model used throughout this thesis assumes that additional semiconductor production capacity can be added at any time, and that there is no relationship between the amount of capacity ordered and the delivery of that capacity. In reality, the semiconductor equipment industry is subject to its own cycles of under and over capacity which are amplified versions of the growth cycles experienced by semiconductor producers. The introduction of new generations of semiconductor equipment such as photo-lithographic steppers or plasma etchers creates huge increases in demand for these products. If the equipment suppliers boost staff and production capacity to meet the demand for their products during boom times they will have to cut back severely or they will go out of business during lulls in the growth of the semiconductor industry. Modeling the technology supply chain back towards the capital equipment makers and forward toward the computer and consumer electronics manufacturers could provide further insight into the underlying causes of the dynamics of the industry.

### 4.2.6 Firm Models Vs Industry Models

The present model is an industry model in that all players in the industry use the same rules for setting pricing and capital investment. Clearly different firms within the industry make different investment decisions. Intel is very aggressive about investments in capital equipment and R&D necessary to produce high performance microprocessors in the latest processes while Micron Technology builds DRAMs in more mature technologies which are farther down the learning curve. Still other firms like Weitech and Chips and Technologies don't even do their own manufacturing. Instead they rely on their ability to purchase excess semiconductor capacity from other manufacturers. In order to model the effect of these different approaches to semiconductor manufacturing it would be necessary to allow differences in policy decisions between different sectors of the industry. The capital investment needs of an innovator in semiconductor manufacturing will be quite different from a low cost supplier who is producing commodity parts in an established technology. Duplicating the model for pricing and investment decisions could provide for differences between segments of the industry and would allow comparison of various strategies which a single firm could take against the background of the investment decisions made by the industry as a whole.

### 4.2.7 Dis-aggregation Along Regional Boundaries

The DRAM crisis brought home to US manufacturers the fact that semiconductors are a global market. Recent reports of investments by Korean semiconductor manufacturers emphasize the fact that strong demand for Korean electronic products is driving Samsung and others to invest heavily in new plants and equipment[WSJ, March 14, 1995]. Meanwhile, Japanese electronic manufacturers are getting out of consumer products and shifting their production to computers and other high value products.[7] Japanese manufacturers have been noticeably absent from the recent round of announcements of $1 billion investments in new semiconductor manufacturing facilities. Clearly the decisions of a manager in a country whose economy is growing steadily at nine percent per year will be different than those of a manager in a country which is subjected to an extended recession. Dis-aggregating the model into two or more regional blocks could better predict the differences in patterns of demand growth between regions and help to understand the dynamics of semiconductor manufacturing and trade between the regions.

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[7] Dr. Yukio Mizuno, Executive Advisor to Chairman of NEC Corporation, personal communication.

# 5. Summary and Conclusions

At each stage of the analysis in Chapter 3, conclusions have been drawn about the adequacy of the model in determining the reasons behind the patterns of growth within the semiconductor industry. In the discussion that follows, these conclusions will be expanded to include a comparison of the model runs for each of the major effects which has been explored.

## *5.1 Patterns of Growth in the Semiconductor Industry*

The worldwide semiconductor industry yearly sales have grown by 14.9 percent per year between 1980 and 1994. Half of that growth can be accounted for by a GDP multiplier effect which ties growth in demand for semiconductors to a multiple of the overall growth variations of Gross Domestic Product in the consuming countries. Most of the rest of the industry growth can be accounted for by a technology effect which increases demand for new products based on the availability of new technologies. In this thesis only one new technology was introduced in the 1983-84 time frame. The model predicted billings (sales) and book to bill ratio closely track the SIA reported data up until the 1987-88 time frame at which point a lack of technology improvement in the model causes the industry revenues to begin to fluctuate with the kinds of

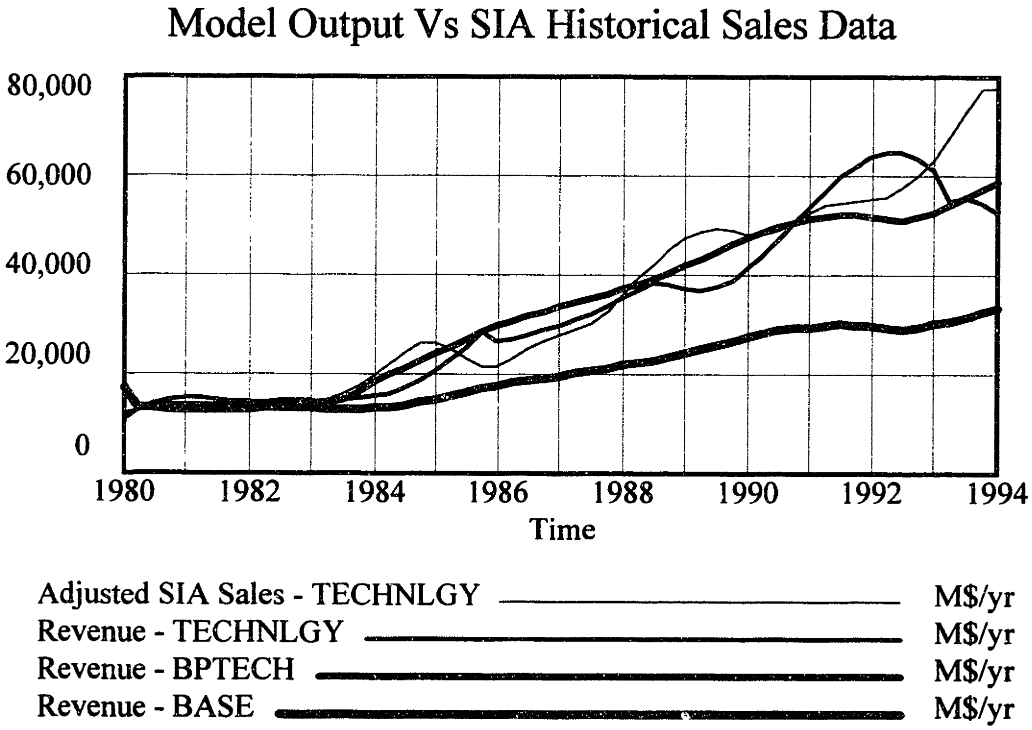

**Figure 5.1 - The Causes of Growth in the Semiconductor Industry.**

growth and decline cycles which are characteristic of commoditized products.

The model output shown in Figure 5.1 illustrates the relative contribution of each of the three major effects which were examined in the model. The run labeled BASE is the model output with only the GDP multiplier effect turned on. The run labeled BPTECH adds the effect of the technology transition in 1983-84 to the GDP multiplier. The run labeled TECHNLGY adds in all of the effects which have been discussed, including the effect of backlog, the effect of price discounting due to over-capacity, and the effects of perceived margins on investment, demand forecast and asset life. As can be seen from Figure 5.1, the GDP and Technology effects contribute most of the long term growth which has occurred in the semiconductor industry while the pricing and margin effects contribute most of the variation in growth.

## *5.2 Implications for Policy Makers*

What does this all mean to policy makers in the semiconductor industry? I believe that three main conclusions can be drawn. First, the continual advancement of semiconductor technology is a major driver of growth in the industry. Any company which falls behind in developing new technology and rapidly putting it into production will soon find itself subjected to severe price discounting due to the inherently lower manufacturing cost of newer technologies. Rapid growth covers up many mistakes in capacity planning in the semiconductor industry. The excess capacity of 1985, which lead to severe losses in the industry in 1986, was absorbed by 1987 as DRAM prices stabilized and American manufacturers moved into new markets. Companies which do not aggressively move into manufacturing of new technologies are subject to severe price competition due to commoditization effects. New technology generations are introduced every three years. Within three years of introduction, the cost per function of the new technology has dropped below that of the technology it has replaced. Any manufacturer who fails to move to a new technology generation will be unable to compete on part price with manufacturers who have kept on the technology curve. This is the long run view of semiconductor manufacturing, keep on the technology curve or get out of business.

The second major conclusion which can be drawn from the model is that growth in semiconductor demand is quite sensitive to general economic cycles. In doing long range planning, managers should pay attention to the global economic cycles. The growth in technology capability since 1980 has resulted in 1000 times more functionality for less than ten times the price, a 100x improvement in cost per function. This level of productivity improvement has allowed economical uses of semiconductors in products like automobiles and home computers which are major purchases for consumers. Purchase of a major consumer item is much more likely to be postponed during an economic downturn, even if attractive new technology is available. This means that the link between semiconductor demand and economic cycles is likely to become more pronounced in coming years. VLSI Research Inc., a consulting firm with a good track record for predicting year to year growth variations in the semiconductor industry, has stated that 1995 will be a year of sales decline in the semiconductor industry because of the confluence of a technology transition and an economic downturn [Hutcheson, January 1995]. If the economic downturn does not occur, because the Federal Reserve succeeds in engineering a "soft landing", the predicted negative sales growth may not happen. However, if sales do decline it could severely effect the revenues of semiconductor companies that were counting on a continuation of the current expansion of demand for semiconductors which began in 1992.

The third major conclusion which can be drawn from the analysis in this thesis is that most of the volatility in semiconductor demand is tied to the effects of price fluctuations due to under and over capacity in the global market. These fluctuations are exacerbated by the effects of semiconductor manufacturers making investments for other than economic reasons. If the Korean manufacturers believe that they are making a strategic investment in DRAMs and will take DRAM market share from the Japanese, then they may well invest more heavily in manufacturing capacity than they would if they were only counting on economic growth to boost demand for their products. It is unlikely that Japanese semiconductor manufacturers who remember the 4 billion dollars in losses they incurred during the DRAM crisis of the mid 1980s would make the same type of strategic investment with the state of the Japanese economy today. Managers should closely track the availability of semiconductor capacity in the worldwide industry, and use that data in making capacity investment decisions. The SIA announced plans earlier this year to begin tracking data on available square inches of silicon wafer capacity worldwide. This data should be used in conjunction with announced expansion plans of semiconductor companies worldwide as a basis for modeling the results of managers own investment decisions on future price fluctuations for semiconductor products.

The economies of the world have become more interdependent. The effects of macroeconomic cycles are no longer limited to a single economy. Global recessions such as the one in 1991 effect demand in all markets, and cause managers worldwide to make similar investment decisions. Most American and European companies are looking toward South East Asia for growth opportunities. Countries such as Korea, Singapore and Taiwan have growth rates greater than twice that of the US. Managers in these countries are likely to be aggressive in adding semiconductor manufacturing capacity if they expect these growth rates to continue. If history repeats itself, today's shortage of capacity will turn into a capacity glut in the near future. Strategic partnerships with Asian manufacturers could allow US semiconductor suppliers to hedge against the next downturn and reduce the severity of the next capacity crisis by reducing the magnitude of the global over-investment in capacity.

The good news which the analysis carried out in this thesis proclaims is that the semiconductor industry has been spared from the effects of commoditization by the rapid rate of technological progress. However, the cost of staying on the leading edge of that technological progress is increasing to the point where even Gordon Moore doubts that the rate of progress can be economically maintained. This thesis is a step in the direction of understanding the causes of fluctuations in growth of the worldwide semiconductor industry. The rising cost of capital equipment will eventually halt the improvements in cost per function which have been characteristic of the industry for the last forty years. Any company which can accurately predict when the turning point will come will be in a position to benefit from that knowledge. For any prediction to be valid, it must be founded in a realistic model of the underlying dynamics of the semiconductor industry. This thesis provides a first step towards such a model, however, much has yet to be done before a reliable prediction can be made.

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## Semiconductor Industry Statistics

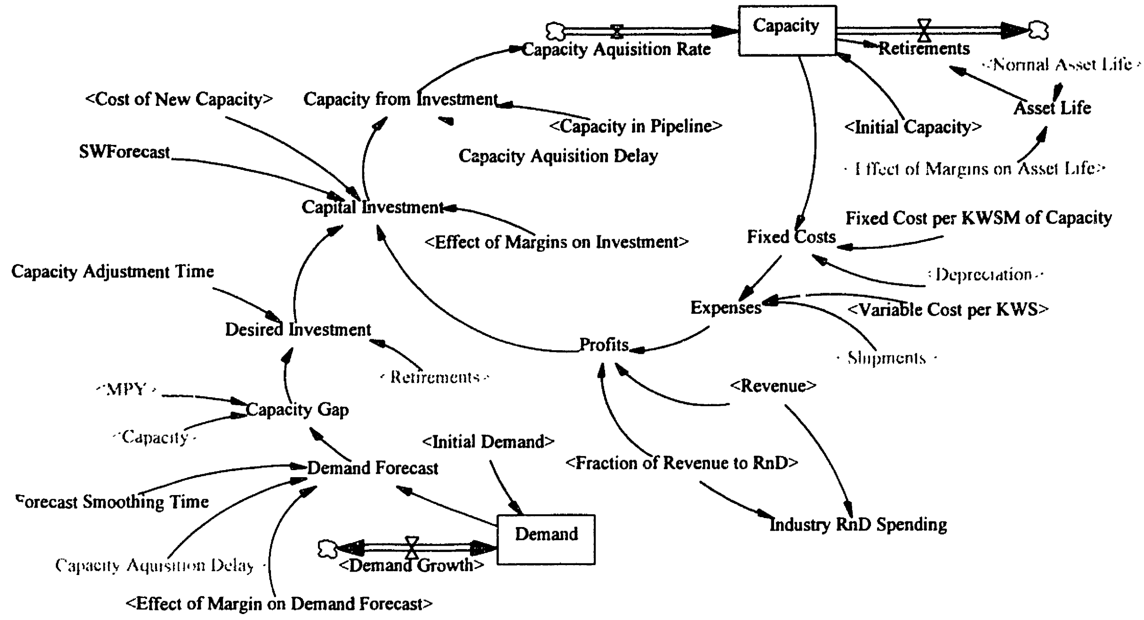
### Bookings and Billings

The table below shows the evolution of the semiconductor trade statistics collected and supported by the Semiconductor Industry Association (SIA).

| Year | Reporting Body | Report Title | Comments |
|---|---|---|---|
| 1973 - 1975 | WEMA Semiconductor Marketing Statistical Program | Worldwide Shipments by US Based Semiconductor Manufacturers | Only yearly statistics reported for US manufacturers only |
| 1976 | WEMA - Price Waterhouse publishers | Worldwide Shipments and Bookings by US Based Semiconductor Manufacturers | Billings reported monthly, bookings reported quarterly |
| 1977 | SIA Semiconductor Trade Statistics | Worldwide Shipments, Bookings and Backlog by US Based Semi-Conductor Manufacturers | SIA took over, added MOS and Bipolar memory |
| 1978 | SIA Semiconductor Trade Statistics | Worldwide Shipments, Bookings and Backlog by US Based Semi-Conductor Manufacturers | Administered by SIA, compiled by Price Waterhouse |
| 1980 | Semiconductor Trade Statistics Program STSP | Worldwide Shipments, Bookings and Backlog by US and European based Semiconductor Manufacturers | US and European statistics combined, no separate US report |
| 1981 | STSP | Worldwide Shipments, Bookings and Backlog by US and European based Semiconductor Manufacturers | Detail added to Total Digital MOS Memory |
| 1982 - 1983 | STSP | Worldwide Shipments, Bookings and Backlog by US and European based Semiconductor Manufacturers | Added Total Digital MOS Logic, Total Digital CMOS |
| 1984 | Worldwide Semiconductor Trade Statistics, WSTS | Worldwide Shipments and Bookings by US, European and Japanese based Semiconductor Manufacturers. | Japanese shipments added. Administered by SIA, compiled by Price Waterhouse |
| 1985 | WSTS - Compiled by Price Waterhouse and Tohamatsu Awoki & Co. | Worldwide Shipments and Bookings by US, European and Japanese based Semiconductor Manufacturers. | SRAM and DRAM numbers combined for confidentiality |
| 1986 | WSTS | Worldwide Shipments and Bookings by US, European and Japanese based Semiconductor Manufacturers. | Separated Gate Array and Standard Cell Logic |
| 1987 - 1991 | WSTS | Worldwide Shipments and Bookings by US, European and Japanese based Semiconductor Manufacturers. | |
| 1992 - | WSTS | Worldwide Sales and Orders by US, Europe, Japanese and Asia based Semiconductor Manufacturers | |

## Model Diagrams and Documentation

### Main Sector (Thesis2)



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.thesis2

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(177) Capacity =
INTEG( Capacity Aquisition Rate
- Retirements ,
Initial Capacity )
Units: KWSM
Yearly industry Wide capacity in Thousands of 6" equivalent Wafer Starts per Month
(180)Capacity Aquisition Rate - Rate at which worldwide capacity is added. Measured in capacity units/yr. Capacity is measured in KWSM.
(096)Initial Capacity - Industry wide wafer capacity at start of modeling period in thousands of 6" equivalent Wafer Starts per Month
(192)Retirements - Rate at which capacity is being retired form use in production.

(178) Capacity Adjustment Time = 1
Units: yr
Time over which management chooses to close the capacity gap.

(179) Capacity Aquisition Delay = 1.5
Units: yr
Delay between ordering wafer capacity and bringing it on line.

(180) Capacity Aquisition Rate =
Capacity from Investment

Units: KWSM/yr
Rate at which worldwide capacity is added. Measured in capacity units/yr. Capacity is measured in KWSM.
(181)Capacity from Investment - Capacity brought on line through investment activities.

(181) Capacity from Investment =
DELAY3I ( Capital Investment ,
Capacity Aquisition Delay ,
Capacity in Pipeline )
Units: KWSM/yr
Capacity brought on line through investment activities.
(179)Capacity Aquisition Delay - Delay between ordering wafer capacity and bringing it on line.
(090)Capacity in Pipeline - Amount of capacity that is in the pipeline to come online after the model initializes.
(183)Capital Investment - Investment assumption is that all industry wide profit is fed back into creating new capacity. This model ignores the demand forecast if SWForecast is set to 0.

(182) Capacity Gap =
Demand Forecast
/ MPY
- Capacity
Units: KWSM
Gap between installed capacity and capacity required to meet forecast demand.
(177)Capacity - Yearly industry Wide capacity in Thousands of 6" equivalent Wafer Starts per Month
(185)Demand Forecast - Forecast of industry demand at future time = Forecasting Horizon
(100)MPY - Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)

(183) Capital Investment =
( 1
- SWForecast )
* Profits
/ Cost of New Capacity
+ SWForecast
* Desired Investment
* Effect of Margins on Investment
Units: KWSM/yr
Investment assumption is that all industry wide profit is fed back into creating new capacity. This model ignores the demand forecast if SWForecast is set to 0.
(091)Cost of New Capacity - Cost of additional capacity measured in $Million/KWSM. Assumes 1985 average price level of $200 Million for a 20KWSM 6" fab. If WSRisingCapCost is set non-zero, the cost will vary with time.
(186)Desired Investment - Desired investment is enough capacity to replace retirements and close the capacity gap within the capacity adjustment time.
(109)Effect of Margins on Investment - If perceived margins are above target margins, then more investment will be attracted to the industry. If perceived margins are below target margin then additional investment will be discouraged.
(191)Profits - Profits are Revenue minus expenses minus R&D spending
(193)SWForecast - A boolean variable which disconnects the forecast from investment decisions. SWForecast = 0 means forecast has no effect on investment, SWForecast = 1 means forecast effects investment

(184) Demand =
INTEG( Demand Growth ,

Initial Demand )
Units: KWS/yr
Yearly Industry wide demand for silicon product in Thousands of 6" equivalent Wafer Starts.
(025)Demand Growth - Net rate of demand growth for Semiconductor Industry assuming compound growth.
(097)Initial Demand - Industry wide demand in Thousands of 6" equivalent Wafer Starts per year. Calculated from initial supply adjusted by book to bill ratio

(185) Demand Forecast =
FORECAST ( Demand ,
Forecast Smoothing Time ,
Capacity Aquisition Delay )
* Effect of Margin on Demand Forecast
Units: KWS/yr
Forecast of industry demand at future time = Forecasting Horizon
(184)Demand - Yearly Industry wide demand for silicon product in Thousands of 6" equivalent Wafer Starts.
(179)Capacity Aquisition Delay - Delay between ordering wafer capacity and bringing it on line.
(107)Effect of Margin on Demand Forecast - If profits are poor, margin drops below target margin and demand forecasts are discounted. If profits are good, forecasts are inflated.
(189)Forecast Smoothing Time - Time over which forecast is smoothed. Larger smoothing times give more weight to older data.

(186) Desired Investment =
Capacity Gap
/ Capacity Adjustment Time
+ Retirements
Units: KWSM/yr
Desired investment is enough capacity to replace retirements and close the capacity gap within the capacity adjustment time.
(178)Capacity Adjustment Time - Time over which management chooses to close the capacity gap.
(182)Capacity Gap - Gap between installed capacity and capacity required to meet forecast demand.
(192)Retirements - Rate at which capacity is being retired form use in production.

(187) Expenses =
Fixed Costs
+ Shipments
* Variable Cost per KWS
Units: M$/yr
Yearly Expenses associated with semiconductor manufacturing.
(083)Fixed Costs - Fixed cost allocated to capacity.
(041)Shipments - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.
(023)Variable Cost per KWS - Cost of materials and labor in millions of dollars per thousand wafers produced per week.

(188) Fixed Cost per KWSM of Capacity = 2.47
Units: M$/(yr*KWSM)
Fixed costs associated with wafer capacity over and above depretiation expense.

(189) Forecast Smoothing Time = 0.25
Units: yr

Time over which forecast is smoothed. Larger smoothing times give more weight to older data.

(190) Industry RnD Spending =
Revenue
* Fraction of Revenue to RnD
Units: M$/yr
Amount of industry revenues spent on process R&D.
(092)Fraction of Revenue to RnD - Percentage of industry revenue devoted to RnD.
SWIndustryRnD turns off RnD expenses. If SWIndustryRnD = 0, Fraction of Revenue to RnD = 0.
(130)Revenue - Yearly revenue from sale of semiconductor product.

(191) Profits =
Revenue
* ( 1
- Fraction of Revenue to RnD )
- Expenses
Units: M$/yr
Profits are Revenue minus expenses minus R&D spending
(187)Expenses - Yearly Expenses associated with semiconductor manufacturing.
(092)Fraction of Revenue to RnD - Percentage of industry revenue devoted to RnD.
SWIndustryRnD turns off RnD expenses. If SWIndustryRnD = 0, Fraction of Revenue to RnD = 0.
(130)Revenue - Yearly revenue from sale of semiconductor product.

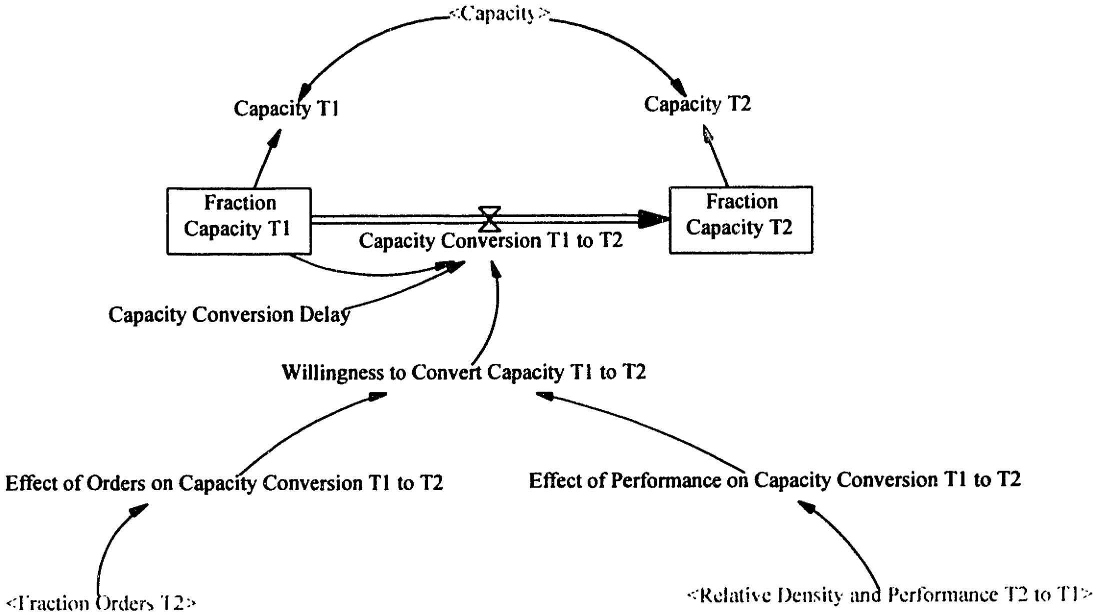
(192) Retirements =
Capacity
/ Asset Life
Units: KWSM/yr
Rate at which capacity is being retired form use in production.
(177)Capacity - Yearly industry Wide capacity in Thousands of 6" equivalent Wafer Starts per Month
(087)Asset Life - Lifetime over which capacity is being retired. If margins are poor, asset lifetimes will be extended. If margins are good, asset lifetimes will be shortened by agressive replacement of equipment

(193) SWForecast = 0
Units: Dimensionless
A boolean variable which disconnects the forecast from investment decisions. SWForecast = 0 means forecast has no effect on investment, SWForecast = 1 means forecast effects investment

(194) T SIA US Capital Expenditures (
[(1979,0)-(2000,8000)],(1980,1400),(1982,2000),(1983,2400),(1984,4400),(1985,3500),(1986,3200),(1987,3800),(1988,4600),(1989,5100),(1990,5800),(1991,5900),(1992,6600),(1995,7600) )
Units: M$/yr
SIA data for capital investments by the US semiconductor industry. 1982-92 data extrapolated to 1980-95 time period

(195) T TEODG (
[(-10,0)-(10,1)],(-10,0),(0,0),(10,1) )
Units: Dimensionless/yr
Effect of increases in technology index on demand growth for semiconductors.

## Capacity Conversion



********************************
.capacity conversion
********************************

(006) Capacity Conversion Delay = 1
Units: yr
Time required to convert capacity, due to equipment ordering delays, etc.

(007) Capacity Conversion T1 to T2 =
Fraction Capacity T1
* Willingness to Convert Capacity T1 to T2
/ Capacity Conversion Delay
Units: Fraction/yr
Rate at which capacity is converted from technology T1 to T2.
(012)Fraction Capacity T1 - Fraction of capacity for technology T1. Assumed to be dominant capacity at begining of simulation.
(006)Capacity Conversion Delay - Time required to convert capacity, due to equipment ordering delays, etc.
(014)Willingness to Convert Capacity T1 to T2 - Willingness to convert capacity index varies between 0 and 1.

(008) Capacity T1 =
Capacity
* Fraction Capacity T1
Units: KWSM
Amount of capacity that is available for production of T1
(177)Capacity - Yearly industry Wide capacity in Thousands of 6" equivalent Wafer Starts per Month
(012)Fraction Capacity T1 - Fraction of capacity for technology T1. Assumed to be dominant capacity at begining of simulation.

(009) Capacity T2 =
Capacity
* Fraction Capacity T2
Units: KWSM
Amount of capacity that is available for production of T2.
(177)Capacity - Yearly industry Wide capacity in Thousands of 6" equivalent Wafer Starts per Month
(013)Fraction Capacity T2 - Fraction of capacity that is used for production of T2. Assumed to be 0 at begining of the simulation.

(010) Effect of Orders on Capacity Conversion T1 to T2 =
T EOCCT1T2 ( Fraction Orders T2 )
Units: Dimensionless
As orders for T2 grow, more capacity will be converted. There is no perception delay in determining fraction of orders for T1, because manufacturers are booking the orders.
(163)Fraction Orders T2 - Fraction of orders for technology T2, assumed to be 0 at begining of simulation.
(143)T EOCCT1T2 - As perceived orders for T2 increase as a fraction of total orders, more capacity will be converted to T2

(011) Effect of Performance on Capacity Conversion T1 to T2 =
T EPCCT1T2 ( Relative Density and Performance T2 to T1 )
Units: Dimensionless
Managers will convert capacity to new technology in anticipation of demand growth.
(170)Relative Density and Performance T2 to T1 - Ratio of the density performance index of T2 to that of T1. A measure of how much better T2 is than T1.
(144)T EPCCT1T2 - Effect of Performance on Capacity Conversion from T1 to T2. As Relative Performance increases, capacity will be converted in anticipation of user needs.

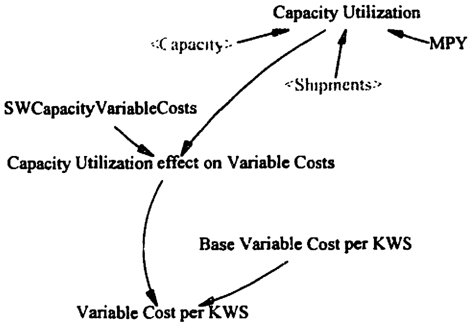
(012) Fraction Capacity T1 =
INTEG( - Capacity Conversion T1 to T2 ,
1)
Units: Fraction
Fraction of capacity for technology T1. Assumed to be dominant capacity at begining of simulation.
(007)Capacity Conversion T1 to T2 - Rate at which capacity is converted from technology T1 to T2.

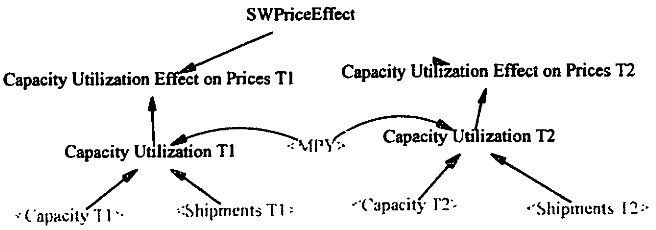
(013) Fraction Capacity T2 =
INTEG( Capacity Conversion T1 to T2 ,
0)
Units: Fraction
Fraction of capacity that is used for production of T2. Assumed to be 0 at begining of the simulation.
(007)Capacity Conversion T1 to T2 - Rate at which capacity is converted from technology T1 to T2.

(014) Willingness to Convert Capacity T1 to T2 =
Effect of Orders on Capacity Conversion T1 to T2
* Effect of Performance on Capacity Conversion T1 to T2
Units: Dimensionless
Willingness to convert capacity index varies between 0 and 1.

(010)Effect of Orders on Capacity Conversion T1 to T2 - As orders for T2 grow, more capacity will be converted. There is no perception delay in determining fraction of orders for T1, because manufacturers are booking the orders.
(011)Effect of Performance on Capacity Conversion T1 to T2 - Managers will convert capacity to new technology in anticipation of demand growth.

## Capacity Utilization





********************************
.capacity utilization
********************************

(015) Base Variable Cost per KWS = 0.288
Units: M$/KWS
Base variable cost per wafer estimated at 34% of sales.

(016) Capacity Utilization =
Shipments
/ ( Capacity
* MPY )
Units: Fraction
Fraction of current capacity required to supply current demand.
(177)Capacity - Yearly industry Wide capacity in Thousands of 6" equivalent Wafer Starts per Month
(100)MPY - Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)
(041)Shipments - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(017) Capacity Utilization Effect on Prices T1 =
IF THEN ELSE ( SWPriceEffect
= 0,
1,
T CUEOP ( Capacity Utilization T1 ) )
Units: Dimensionless
If capacity utilization equals target (implicit target of 100%), CUEOP equals 1. Capacity below target leads to price reductions and capacity above target leads to price increases.
(020)Capacity Utilization T1 - Fraction of current capacity required to supply current demand.
(032)SWPriceEffect - Testing switch that removes price effect when set to 0 and allows price effect when set to 1.
(136)T CUEOP - Capacity Utilization Effect on Prices, When capacity utilization is greater than 1, prices rise rapidly, when capacity utilization drops below 1, prices drop toward marginal cost.

(018) Capacity Utilization Effect on Prices T2 =
IF THEN ELSE ( SWPriceEffect
= 0,
1,
T CUEOP ( Capacity Utilization T2 ) )
Units: Dimensionless
If capacity utilization equals target (implicit target of 100%), CUEOP equals 1. Capacity below target leads to price reductions and capacity above target leads to price increases.
(021)Capacity Utilization T2 - Fraction of current capacity required to supply current demand.
(032)SWPriceEffect - Testing switch that removes price effect when set to 0 and allows price effect when set to 1.
(136)T CUEOP - Capacity Utilization Effect on Prices, When capacity utilization is greater than 1, prices rise rapidly, when capacity utilization drops below 1, prices drop toward marginal cost.

(019) Capacity Utilization effect on Variable Costs =
IF THEN ELSE ( SWCapacityVariableCosts
= 0,
1,
T CUEOVC ( Capacity Utilization ) )
Units: Dimensionless
As capacity utilization rises above target of 90% variable costs begin to rise as extra shifts are hired. Capacity utilization below 70% causes firms to reduce labor inputs.
(016)Capacity Utilization - Fraction of current capacity required to supply current demand.
(022)SWCapacityVariableCosts - If SWCapacityVariableCosts = 0, the capacity effect on Variable Costs is turned off, otherwise it is turned on,
(137)T CUEOVC - As capacity utilization rises above target of 90% variable costs begin to rise as extra shifts are hired. Capacity utilization below 70% causes firms to reduce labor inputs.

(020) Capacity Utilization T1 =
Shipments T1
/ ( Capacity T1
* MPY )
Units: Fraction
Fraction of current capacity required to supply current demand.
(008)Capacity T1 - Amount of capacity that is available for production of T1
(100)MPY - Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)
(051)Shipments T1 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

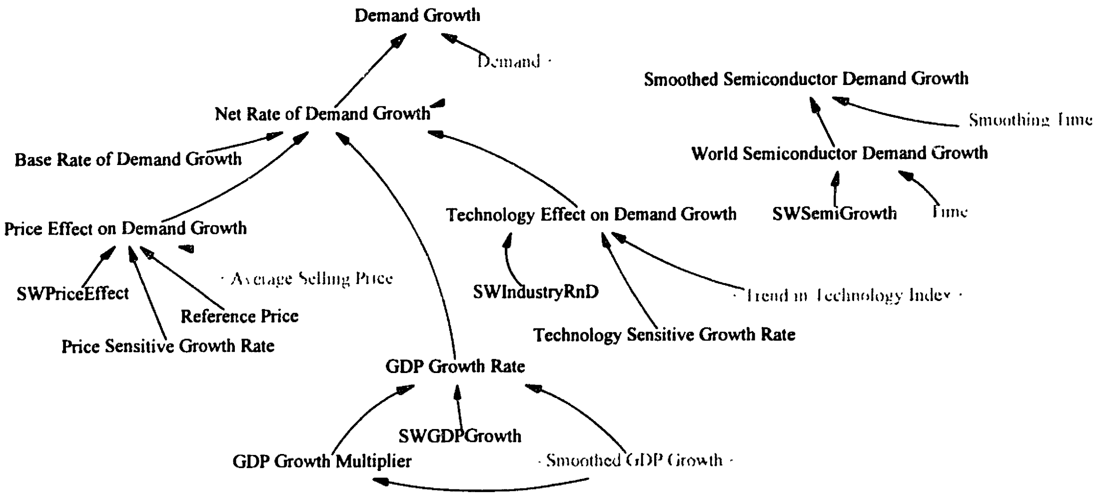
(021) Capacity Utilization T2 =
XIDZ ( Shipments T2 ,
( Capacity T2
* MPY ) ,
1)
Units: Fraction
Fraction of current capacity required to supply current demand.
(009)Capacity T2 - Amount of capacity that is available for production of T2.
(100)MPY - Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)
(061)Shipments T2 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(022) SWCapacityVariableCosts = 0
Units: Dimensionless

If SWCapacityVariableCosts = 0, the capacity effect on Variable Costs is turned off, otherwise it is turned on,

(023) Variable Cost per KWS =
Base Variable Cost per KWS
* Capacity Utilization effect on Variable Costs
Units: M$/KWS
Cost of materials and labor in millions of dollars per thousand wafers produced per week.
(015)Base Variable Cost per KWS - Base variable cost per wafer estimated at 34% of sales.
(019)Capacity Utilization effect on Variable Costs - As capacity utilization rises above target of 90% variable costs begin to rise as extra shifts are hired. Capacity utilization below 70% causes firms to reduce labor inputs.

## Demand Growth



********************************
.demand growth
********************************

(024) Base Rate of Demand Growth = 0
Units: 1/yr
Historic average annual rate of demand growth for semconductor industry over period of simulation. Measured from WSTS billings data assuming constant wafer price.

(025) Demand Growth =
Demand
* ( Net Rate of Demand Growth )
Units: KWS/(yr*yr)
Net rate of demand growth for Semiconductor Industry assuming compound growth.
(184)Demand - Yearly Industry wide demand for silicon product in Thousands of 6" equivalent Wafer Starts.
(028)Net Rate of Demand Growth - Net rate of demand growth from all factors, expressed in %/yr

(026) GDP Growth Multiplier =
IF THEN ELSE ( Smoothed GDP Growth
< 0,
3.56,

3.56)
Units: Dimensionless
In a growing economy the growth in demand follows the growth of GDP. During a recession, growth is curtailed by a larger multiplier.
(072)Smoothed GDP Growth - Smoothed US GDP growth, smoothed over 1/2 year.

(027) GDP Growth Rate =
IF THEN ELSE ( SWGDPGrowth
= 0,
0,
Smoothed GDP Growth
* GDP Growth Multiplier )
Units: 1/yr
If SWGDPGrowth is 0, GDP Growth rate is 0, otherwise it is set to US GDP Growth rate.
(026)GDP Growth Multiplier - In a growing economy the growth in demand follows the growth of GDP. During a recession, growth is curtailed by a larger multiplier.
(072)Smoothed GDP Growth - Smoothed US GDP growth, smoothed over 1/2 year.
(031)SWGDPGrowth - SWGDPGrowth turns on (if nonzero) and off (if = 0) the effect of GDP growth on the model

(028) Net Rate of Demand Growth =
( Base Rate of Demand Growth
+ Price Effect on Demand Growth
+ GDP Growth Rate
+ Smoothed Semiconductor Demand Growth
+ Technology Effect on Demand Growth )
Units: 1/yr
Net rate of demand growth from all factors, expressed in %/yr
(024)Base Rate of Demand Growth - Historic average annual rate of demand growth for semconductor industry over period of simulation. Measured from WSTS billings data assuming constant wafer price.
(027)GDP Growth Rate - If SWGDPGrowth is 0, GDP Growth rate is 0, otherwise it is set to US GDP Growth rate.
(029)Price Effect on Demand Growth - If prices drop below reference price demand is stimulated. If prices increase above reference price demand is slowed. If SWPriceEffect=0 the price effect is set to 0.
(073)Smoothed Semiconductor Demand Growth - Smoothed world semiconductor demand growth.
(033)Technology Effect on Demand Growth - As the technology index improves, demand for semiconductors grows because new applications are possible which couldn't have been accomplished with the old technology.

(029) Price Effect on Demand Growth =
IF THEN ELSE ( SWPriceEffect
= 0,
0,
T PEODG ( Average Selling Price
/ Reference Price )
* Price Sensitive Growth Rate )
Units: 1/yr
If prices drop below reference price demand is stimulated. If prices increase above reference price demand is slowed. If SWPriceEffect=0 the price effect is set to 0.
(116)Average Selling Price - Average Selling Price of all semiconductor technologies.

(030)Price Sensitive Growth Rate - Portion of demand growth than can be attributed to price variations.
(129)Reference Price - Reference price in this model is asumed to be a constant over time. It is measured in Millions of $ per Thousand Wafer Starts
(032)SWPriceEffect - Testing switch that removes price effect when set to 0 and allows price effect when set to 1.
(147)T PEODG - Price Effect on Demand Growth - Price sensitivity of demand, normalized. As price drops below 1, demand rises rapidly. As price increases above 1, demand falls off gradually.

(030) Price Sensitive Growth Rate = 0.1
Units: 1/yr
Portion of demand growth than can be attributed to price variations.

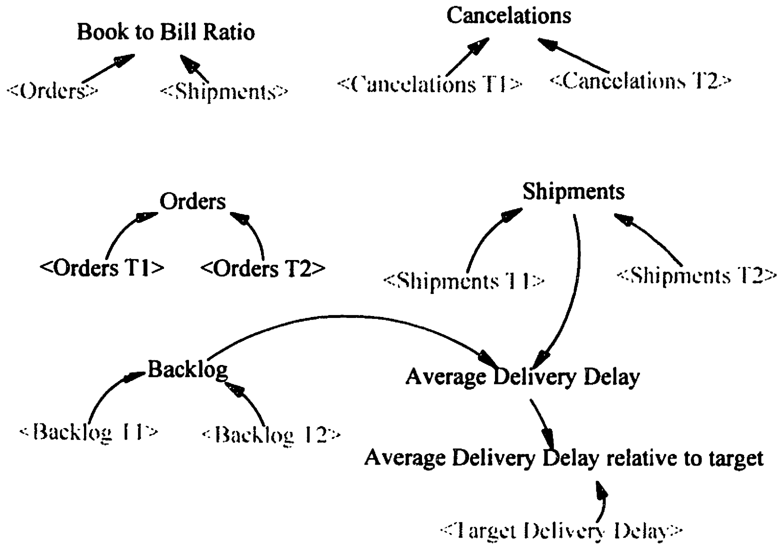
(031) SWGDPGrowth = 0
Units: Dimensionless
SWGDPGrowth turns on (if nonzero) and off (if = 0) the effect of GDP growth on the model

(032) SWPriceEffect = 0
Units: Dimensionless
Testing switch that removes price effect when set to 0 and allows price effect when set to 1.

(033) Technology Effect on Demand Growth =
IF THEN ELSE ( SWIndustryRnD
= 0,
0,
Technology Sensitive Growth Rate
* T TEODG ( Trend in Technology Index ) )
Units: 1/yr
As the technology index improves, demand for semiconductors grows because new applications are possible which couldn't have been accomplished with the old technology.
(103)SWIndustryRnD - If SWIndustryRnD = 0 the R&D effects are turned off, otherwise they are turned on.
(034)Technology Sensitive Growth Rate - Growth rate due to increases in technology.
(175)Trend in Technology Index - Growth rate in technology averaged over the Index Smoothing Time.
(195)T TEODG - Effect of increases in technology index on demand growth for semiconductors.

(034) Technology Sensitive Growth Rate = 0.1
Units: 1/yr
Growth rate due to increases in technology.

## Distribution (for aggregate technology)



*********************************
.distribution
*********************************

(035) Average Delivery Delay =
Backlog
/ Shipments
Units: yr
Average Delivery Delay of all technologies.
(037)Backlog - Industry backlog is the sum of the backlogs for all technologies.
(041)Shipments - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(036) Average Delivery Delay relative to target =
Average Delivery Delay
/ Target Delivery Delay
Units: Dimensionless
Relative delivery delay averaged for all technologies.
(035)Average Delivery Delay - Average Delivery Delay of all technologies.
(105)Target Delivery Delay - Target delay between receipt of customer order and shipment product to customer.

(037) Backlog =
Backlog T1
+ Backlog T2
Units: KWS
Industry backlog is the sum of the backlogs for all technologies.
(044)Backlog T1 - Backlog of customer orders which have not yet been shipped or canceled.
(054)Backlog T2 - Backlog of customer orders for technology T2 which have not yet been shipped or canceled. Assumed to be 0 at start of the simulation.

(038) Book to Bill Ratio =

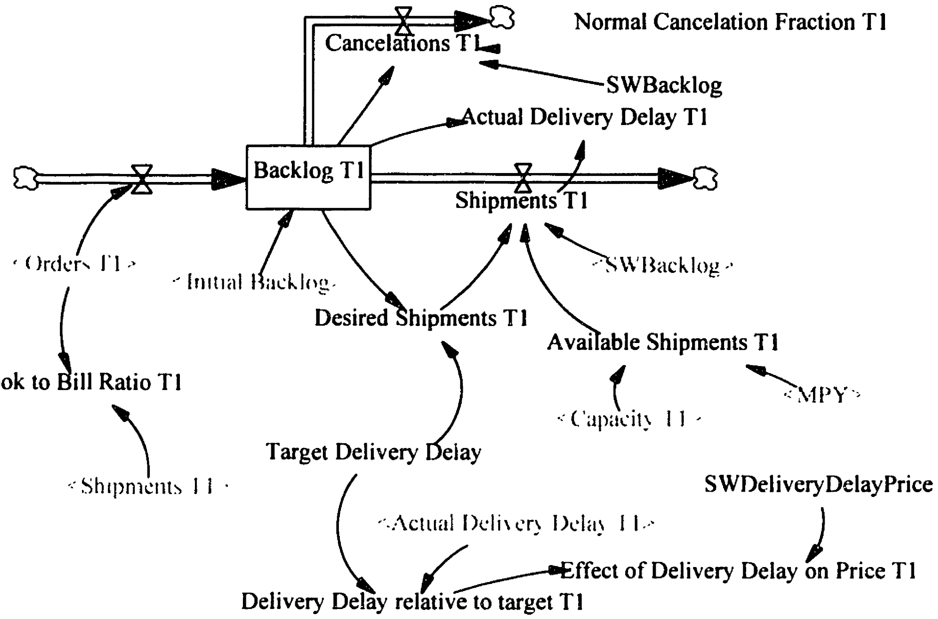
Orders
/ Shipments
Units: Dimensionless
Ratio of the Orders (Bookings) for semiconductor product divided by the shipments (Billings).
(040)Orders - Rate at which customers order semiconductor product. Set to industry demand plus an effect of overbooking due to increased delivery delays.
(041)Shipments - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(039) Cancelations =
Cancelations T1
+ Cancelations T2
Units: KWS/yr
If SWBacklog = 0, cancelations are 0. If SWBacklog = 1, cancelations are computed as a normal cancelation fraction times backlog plus cancelation of phantom orders.
(046)Cancelations T1 - If SWBacklog = 0, cancelations are 0. If SWBacklog = 1, cancelations are computed as a normal cancelation fraction times backlog plus cancelation of phantom orders.
(056)Cancelations T2 - If SWBacklog = 0, cancelations are 0. If SWBacklog = 1, cancelations are computed as a normal cancelation fraction times backlog plus cancelation of phantom orders.

(040) Orders =
Orders T1
+ Orders T2
Units: KWS/yr
Rate at which customers order semiconductor product. Set to industry demand plus an effect of overbooking due to increased delivery delays.
(168)Orders T1 - Orders for Technology T1 as a fraction of industry orders.
(169)Orders T2 - Orders for technology T2 as a fraction of industry orders

(041) Shipments =
Shipments T1
+ Shipments T2
Units: KWS/yr
If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.
(051)Shipments T1 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.
(061)Shipments T2 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

## Distribution T1



*********************************
.distribution T1
*********************************

(042) Actual Delivery Delay T1 =
Backlog T1
/ Shipments T1
Units: yr
Actual Delivery Delay is length of time required to ship entire backlog at current shipment rate.
(044)Backlog T1 - Backlog of customer orders which have not yet been shipped or canceled.
(051)Shipments T1 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(043) Available Shipments T1 =
Capacity T1
* MPY
Units: KWS/yr
Available Shipments are constrained by capacity available.
(008)Capacity T1 - Amount of capacity that is available for production of T1
(100)MPY - Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)

(044) Backlog T1 =
INTEG( Orders T1
- Shipments T1
- Cancelations T1 ,
Initial Backlog )
Units: KWS
Backlog of customer orders which have not yet been shipped or canceled.

(046)Cancelations T1 - If SWBacklog = 0, cancelations are 0. If SWBacklog = 1, cancelations are computed as a normal cancelation fraction times backlog plus cancelation of phantom orders.
(093)Initial Backlog - Initial Backlog of customer orders which have not yet shipped.
(168)Orders T1 - Orders for Technology T1 as a fraction of industry orders.
(051)Shipments T1 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(045) Book to Bill Ratio T1 =
Orders T1
/ Shipments T1
Units: Dimensionless
Ratio of the Orders (Bookings) for semiconductor product divided by the shipments (Billings).
(168)Orders T1 - Orders for Technology T1 as a fraction of industry orders.
(051)Shipments T1 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(046) Cancelations T1 =
IF THEN ELSE ( SWBacklog
= 0,
0,
Backlog T1
* Normal Cancelation Fraction T1 )
Units: KWS/yr
If SWBacklog = 0, cancelations are 0. If SWBacklog = 1, cancelations are computed as a normal cancelation fraction times backlog plus cancelation of phantom orders.
(044)Backlog T1 - Backlog of customer orders which have not yet been shipped or canceled.
(050)Normal Cancelation Fraction T1 - Normal fraction of backlog which is canceled by customers per year.
(062)SWBacklog - If SWBacklog is 0, backlog and cancelations are turned off. If SWBacklog is 1, backlog and cancelations are turned on.

(047) Delivery Delay relative to target T1 =
Actual Delivery Delay T1
/ Target Delivery Delay
Units: Dimensionless
Ratio of Actual Delivery Delay to Target Delivery Delay
(042)Actual Delivery Delay T1 - Actual Delivery Delay is length of time required to ship entire backlog at current shipment rate.
(105)Target Delivery Delay - Target delay between receipt of customer order and shipment product to customer.

(048) Desired Shipments T1 =
Backlog T1
/ Target Delivery Delay
Units: KWS/yr
Desired shipments based on delays inherent in the production cycle.
(044)Backlog T1 - Backlog of customer orders which have not yet been shipped or canceled.
(105)Target Delivery Delay - Target delay between receipt of customer order and shipment product to customer.

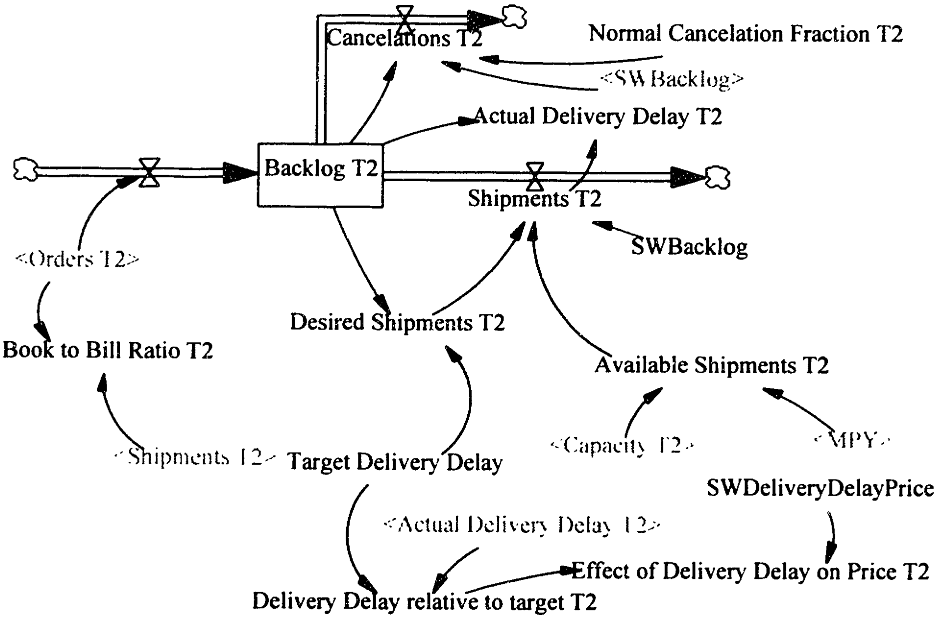
(049) Effect of Delivery Delay on Price T1 =
IF THEN ELSE ( SWDeliveryDelayPrice
= 0,
1,

T CUEOP ( Delivery Delay relative to target T1 ) )
Units: Dimensionless
If the actual delivery delay exceeds target, prices rise. If SWDeliveryDelayPrice is set to 0 the effect is set to 1.
(047)Delivery Delay relative to target T1 - Ratio of Actual Delivery Delay to Target Delivery Delay
(063)SWDeliveryDelayPrice - If SWDeliveryDelayPrice = 0, delivery delay has no effect on prices, otherwise if delivery delay exceeds target delay prices increase.
(136)T CUEOP - Capacity Utilization Effect on Prices, When capacity utilization is greater than 1, prices rise rapidly, when capacity utilization drops below 1, prices drop toward marginal cost.

(050) Normal Cancelation Fraction T1 = 0.1
Units: 1/yr
Normal fraction of backlog which is canceled by customers per year.

(051) Shipments T1 =
IF THEN ELSE ( SWBacklog
= 0,
Desired Shipments T1 ,
MIN ( Desired Shipments T1 ,
Available Shipments T1 ) )
Units: KWS/yr
If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.
(043)Available Shipments T1 - Available Shipments are constrained by capacity available.
(048)Desired Shipments T1 - Desired shipments based on delays inherent in the production cycle.
(062)SWBacklog - If SWBacklog is 0, backlog and cancelations are turned off. If SWBacklog is 1, backlog and cancelations are turned on.

## Distribution T2



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********************************
  .distribution T2
********************************

(052)    Actual Delivery Delay T2 =
     XIDZ ( Backlog T2 ,
        Shipments T2 ,
        1)
          Units: yr
          Actual Delivery Delay is length of time required to ship entire backlog at current shipment rate.
          (054)Backlog T2 - Backlog of customer orders for technology T2 which have not yet been
          shipped or canceled. Assumed to be 0 at start of the simulation.
          (061)Shipments T2 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments
          are constrained to the lesser of desired shipments and available shipments.

(053)    Available Shipments T2 =
      Capacity T2
          * MPY
          Units: KWS/yr
          Available Shipments are constrained by capacity available.
          (009)Capacity T2 - Amount of capacity that is available for production of T2.
          (100)MPY - Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)

(054)    Backlog T2 =
      INTEG( Orders T2
            - Shipments T2
            - Cancelations T2 ,
         0)
          Units: KWS
          Backlog of customer orders for technology T2 which have not yet been shipped or canceled.
          Assumed to be 0 at start of the simulation.
          (056)Cancelations T2 - If SWBacklog = 0, cancelations are 0. If SWBacklog = 1, cancelations are
          computed as a normal cancelation fraction times backlog plus cancelation of phantom orders.
          (169)Orders T2 - Orders for technology T2 as a fraction of industry orders
          (061)Shipments T2 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments
          are constrained to the lesser of desired shipments and available shipments.

(055)    Book to Bill Ratio T2 =
      XIDZ ( Orders T2 ,
         Shipments T2 ,
         1)
          Units: Dimensionless
          Ratio of the Orders (Bookings) for semiconductor product divided by the shipments (Billings).
          (169)Orders T2 - Orders for technology T2 as a fraction of industry orders
          (061)Shipments T2 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments
          are constrained to the lesser of desired shipments and available shipments.

(056)    Cancelations T2 =
      IF THEN ELSE ( SWBacklog
            = 0,
         0,
         Backlog T2
            * Normal Cancelation Fraction T2 )
          Units: KWS/yr
```

If SWBacklog = 0, cancelations are 0. If SWBacklog = 1, cancelations are computed as a normal cancelation fraction times backlog plus cancelation of phantom orders.
(054)Backlog T2 - Backlog of customer orders for technology T2 which have not yet been shipped or canceled. Assumed to be 0 at start of the simulation.
(060)Normal Cancelation Fraction T2 - Normal fraction of backlog which is canceled by customers per year.
(062)SWBacklog - If SWBacklog is 0, backlog and cancelations are turned off. If SWBacklog is 1, backlog and cancelations are turned on.

(057) Delivery Delay relative to target T2 =
Actual Delivery Delay T2
/ Target Delivery Delay
Units: Dimensionless
Ratio of Actual Delivery Delay to Target Delivery Delay
(052)Actual Delivery Delay T2 - Actual Delivery Delay is length of time required to ship entire backlog at current shipment rate.
(105)Target Delivery Delay - Target delay between receipt of customer order and shipment product to customer.

(058) Desired Shipments T2 =
Backlog T2
/ Target Delivery Delay
Units: KWS/yr
Desired shipments based on delays inherent in the production cycle.
(054)Backlog T2 - Backlog of customer orders for technology T2 which have not yet been shipped or canceled. Assumed to be 0 at start of the simulation.
(105)Target Delivery Delay - Target delay between receipt of customer order and shipment product to customer.

(059) Effect of Delivery Delay on Price T2 =
IF THEN ELSE ( SWDeliveryDelayPrice
= 0,
1,
T CUEOP ( Delivery Delay relative to target T2 ) )
Units: Dimensionless
If the actual delivery delay exceeds target, prices rise. If SWDeliveryDelayPrice is set to 0 the effect is set to 1.
(057)Delivery Delay relative to target T2 - Ratio of Actual Delivery Delay to Target Delivery Delay
(063)SWDeliveryDelayPrice - If SWDeliveryDelayPrice = 0, delivery delay has no effect on prices, otherwise if delivery delay exceeds target delay prices increase.
(136)T CUEOP - Capacity Utilization Effect on Prices, When capacity utilization is greater than 1, prices rise rapidly, when capacity utilization drops below 1, prices drop toward marginal cost.

(060) Normal Cancelation Fraction T2 = 0.1
Units: 1/yr
Normal fraction of backlog which is canceled by customers per year.

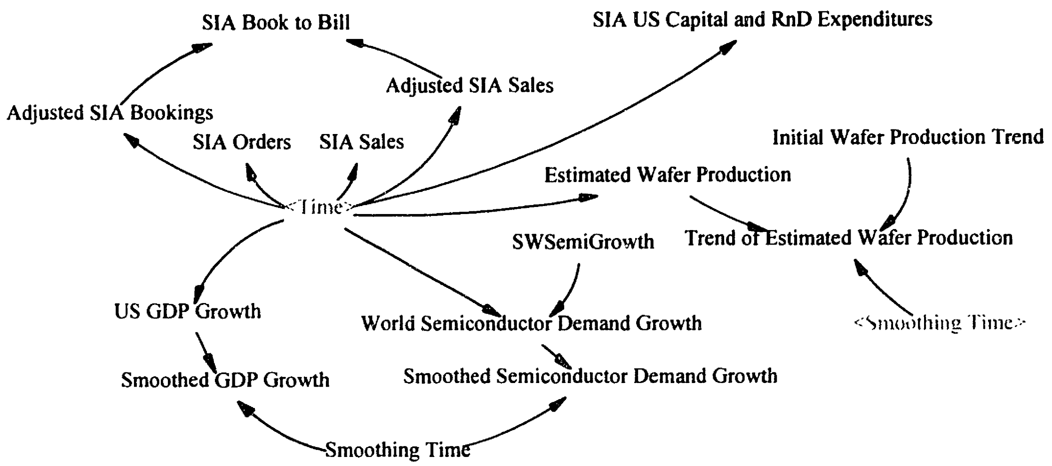
(061) Shipments T2 =
IF THEN ELSE ( SWBacklog
= 0,
Desired Shipments T2 ,
MIN ( Desired Shipments T2 ,
Available Shipments T2 ) )

Units: KWS/yr
If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.
(053)Available Shipments T2 - Available Shipments are constrained by capacity available.
(058)Desired Shipments T2 - Desired shipments based on delays inherent in the production cycle.
(062)SWBacklog - If SWBacklog is 0, backlog and cancelations are turned off. If SWBacklog is 1, backlog and cancelations are turned on.

(062) SWBacklog = 0
Units: Dimensionless
If SWBacklog is 0, backlog and cancelations are turned off. If SWBacklog is 1, backlog and cancelations are turned on.

(063) SWDeliveryDelayPrice = 0
Units: Dimensionless
If SWDeliveryDelayPrice = 0, delivery delay has no effect on prices, otherwise if delivery delay exceeds target delay prices increase.

## External (exogenous) Data



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.external
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(064) Adjusted SIA Bookings =
T ADJUSTED SIA BOOKINGS ( Time )
Units: M$/yr
SIA Booking Data adjusted to include Japanese Manufacturers prior to 1984.
(000)Time - Internally defined simulation time.
(133)T ADJUSTED SIA BOOKINGS - SIA Booking Data adjusted to include Japanese Manufacturers prior to 1984.

(065) Adjusted SIA Sales =
T Adjusted SIA Sales ( Time )
Units: M$/yr
Reference data based on SIA sales, adjusted to include Japanese manufacturers prior to 1984
(000)Time - Internally defined simulation time.

(134)T Adjusted SIA Sales - SIA Sales data adjusted to include Japanese manufacturers prior to 1984

(066) Estimated Wafer Production =
T SIA Demand Estimate ( Time )
Units: KWS/yr
Estimate of yearly 6" equivalent wafer supply per year based on SIA billing data and VLSI Research Inc. wafer demand data.
(000)Time - Internally defined simulation time.
(148)T SIA Demand Estimate - Estimate of yearly 6" equivalent wafer demand per year based on SIA and VLSI Research Inc. data.

(067) Initial Wafer Production Trend = 0
Units: Dimensionless/yr
Initial value of Wafer Production Trend. Used only for calulation of historical trend used as a reference mode.

(068) SIA Book to Bill =
Adjusted SIA Bookings
/ Adjusted SIA Sales
Units: Dimensionless
Ratio of Bookings (orders) to Billings (Sales) for SIA data.
(064)Adjusted SIA Bookings - SIA Booking Data adjusted to include Japanese Manufacturers prior to 1984.
(065)Adjusted SIA Sales - Reference data based on SIA sales, adjusted to include Japanese manufacturers prior to 1984

(069) SIA Orders =
T SIA Orders ( Time )
Units: M$/yr
Table lookup of smoothed SIA yearly booking data
(000)Time - Internally defined simulation time.
(149)T SIA Orders - SIA Yearly Booking data in $ million of orders per year, summed over last 4 quarters. i.e. data for 1981.00 is yearly orders for 1980.

(070) SIA Sales =
T SIA Sales ( Time )
Units: M$/yr
External input of SIA Sales Data.
(000)Time - Internally defined simulation time.
(150)T SIA Sales - SIA data for total semiconductor sales.

(071) SIA US Capital and RnD Expenditures =
T SIA US Capital Expenditures ( Time )
Units: M$/yr
SIA data for capital investments by the US semiconductor industry. 1982-92 data extrapolated to 1980-95 time period
(000)Time - Internally defined simulation time.
(194)T SIA US Capital Expenditures - SIA data for capital investments by the US semiconductor industry. 1982-92 data extrapolated to 1980-95 time period

(072) Smoothed GDP Growth =
SMOOTH ( US GDP Growth ,
Smoothing Time )

Units: 1/yr
Smoothed US GDP growth, smoothed over 1/2 year.
(074)Smoothing Time - Time over which external inputs are smoothed.
(077)US GDP Growth - Average annual US GDP growth rate in %/yr, from World Bank and IMF Statistics.

(073) Smoothed Semiconductor Demand Growth =
SMOOTH ( World Semiconductor Demand Growth ,
Smoothing Time )
Units: 1/yr
Smoothed world semiconductor demand growth.
(074)Smoothing Time - Time over which external inputs are smoothed.
(078)World Semiconductor Demand Growth - World Semiconductor Demand Growth, SIA data.

(074) Smoothing Time = 0.5
Units: yr
Time over which external inputs are smoothed.

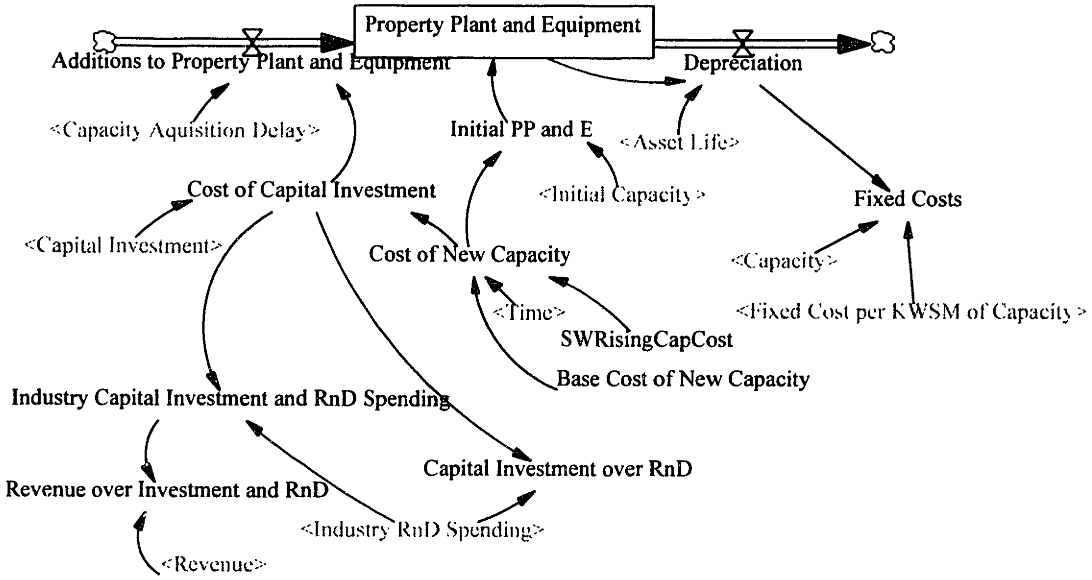
(075) SWSemiGrowth = 0
Units: Dimensionless
If SWSemiGrowth = 0, World Semiconductor Demand growth is turned set to 0, otherwise it is read in from a table.

(076) Trend of Estimated Wafer Production =
TREND ( Estimated Wafer Production ,
Smoothing Time ,
Initial Wafer Production Trend )
Units: 1/yr
Yearly Growth rate of extimated wafer production.
(066)Estimated Wafer Production - Estimate of yearly 6" equivalent wafer supply per year based on SIA billing data and VLSI Research Inc. wafer demand data.
(067)Initial Wafer Production Trend - Initial value of Wafer Production Trend. Used only for calulation of historical trend used as a reference mode.
(074)Smoothing Time - Time over which external inputs are smoothed.

(077) US GDP Growth =
T US GDP Growth ( Time )
Units: 1/yr
Average annual US GDP growth rate in %/yr, from World Bank and IMF Statistics.
(000)Time - Internally defined simulation time.
(152)T US GDP Growth - Average annual GDP Growth for US.

(078) World Semiconductor Demand Growth =
IF THEN ELSE ( SWSemiGrowth
= 0,
0,
T SIA World Growth ( Time ) )
Units: 1/yr
World Semiconductor Demand Growth, SIA data.
(000)Time - Internally defined simulation time.
(075)SWSemiGrowth - If SWSemiGrowth = 0, World Semiconductor Demand growth is turned set to 0, otherwise it is read in from a table.
(151)T SIA World Growth - World semiconductor demand growth, SIA data.

## Financial Sector



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(079) Additions to Property Plant and Equipment =
DELAY3 ( Cost of Capital Investment ,
Capacity Aquisition Delay )
Units: M$/yr
Cost of capacity that has become productive this year.
(179)Capacity Aquisition Delay - Delay between ordering wafer capacity and bringing it on line.
(081)Cost of Capital Investment - Capital cost of new capacity at time investment decision is made.

(080) Capital Investment over RnD =
ZIDZ ( Cost of Capital Investment ,
Industry RnD Spending )
Units: Dimensionless
Ratio of Cost of Capital Equipment to Total Industry RnD spending
(081)Cost of Capital Investment - Capital cost of new capacity at time investment decision is made.
(190)Industry RnD Spending - Amount of industry revenues spent on process R&D.

(081) Cost of Capital Investment =
Capital Investment
* Cost of New Capacity
Units: M$/yr
Capital cost of new capacity at time investment decision is made.
(183)Capital Investment - Investment assumption is that all industry wide profit is fed back into creating new capacity. This model ignores the demand forecast if SWForecast is set to 0.
(091)Cost of New Capacity - Cost of additional capacity measured in $Million/KWSM. Assumes 1985 average price level of $200 Million for a 20KWSM 6" fab. If WSRisingCapCost is set non-zero, the cost will vary with time.

(082) Depreciation =
Property Plant and Equipment
/ Asset Life
Units: M$/yr
The depreciation expense associated the installed base of capacity.
(085)Property Plant and Equipment - Book value of Property Plant and Equipment, carried to determine depretiation costs.
(087)Asset Life - Lifetime over which capacity is being retired. If margins are poor, asset lifetimes will be extended. If margins are good, asset lifetimes will be shortened by agressive replacement of equipment

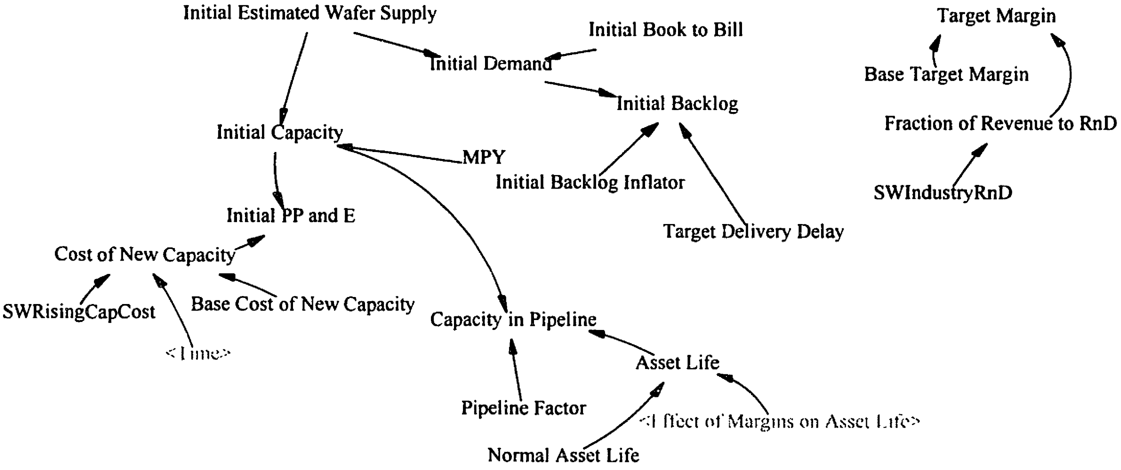
(083) Fixed Costs =
Depreciation
+ Capacity
* Fixed Cost per KWSM of Capacity
Units: M$/yr
Fixed cost allocated to capacity.
(177)Capacity - Yearly industry Wide capacity in Thousands of 6" equivalent Wafer Starts per Month
(082)Depreciation - The depreciation expense associated the installed base of capacity.
(188)Fixed Cost per KWSM of Capacity - Fixed costs associated with wafer capacity over and above depretiation expense.

(084) Industry Capital Investment and RnD Spending =
Cost of Capital Investment
+ Industry RnD Spending
Units: M$/yr
Sum of cost of capital investment and industry RnD Spending.
(081)Cost of Capital Investment - Capital cost of new capacity at time investment decision is made.
(190)Industry RnD Spending - Amount of industry revenues spent on process R&D.

(085) Property Plant and Equipment =
INTEG( Additions to Property Plant and Equipment
- Depreciation ,
Initial PP and E )
Units: M$
Book value of Property Plant and Equipment, carried to determine depretiation costs.
(079)Additions to Property Plant and Equipment - Cost of capacity that has become productive this year.
(082)Depreciation - The depreciation expense associated the installed base of capacity.
(099)Initial PP and E - Value of Property Plant and Equipment at the begining of the simulation.

(086) Revenue over Investment and RnD =
( Revenue )
/ Industry Capital Investment and RnD Spending
Units: Dimensionless
Ratio to Profits to Capital Investments and RnD Spending
(084)Industry Capital Investment and RnD Spending - Sum of cost of capital investment and industry RnD Spending.
(130)Revenue - Yearly revenue from sale of semiconductor product.

## Initialization Sector



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(087) Asset Life =
ACTIVE INITIAL( Normal Asset Life
* Effect of Margins on Asset Life ,
Normal Asset Life )
Units: yr
Lifetime over which capacity is being retired. If margins are poor, asset lifetimes will be extended. If margins are good, asset lifetimes will be shortened by agressive replacement of equipment
(108)Effect of Margins on Asset Life - Lookup table for Effect of Margins on Retirements. Input to table is percieved industry profit margin relative to targets.
(101)Normal Asset Life - Normal depretiation time used to write off capital investments.

(088) Base Cost of New Capacity = 10
Units: M$/KWSM
Cost of Capacity in 1985 when a 20KWSM fab cost $200M. (Source TI)

(089) Base Target Margin = 0.26
Units: Dimensionless
Base Target Margin is the expected profit margin (net margin) without considering R&D expenses.

(090) Capacity in Pipeline =
Pipeline Factor
* Initial Capacity
/ Asset Life
Units: KWSM/yr
Amount of capacity that is in the pipeline to come online after the model initializes.
(087)Asset Life - Lifetime over which capacity is being retired. If margins are poor, asset lifetimes will be extended. If margins are good, asset lifetimes will be shortened by agressive replacement of equipment
(096)Initial Capacity - Industry wide wafer capacity at start of modeling period in thousands of 6" equivalent Wafer Starts per Month
(102)Pipeline Factor - Adjustment factor to capacity contained in pipeline

(091) Cost of New Capacity =
IF THEN ELSE ( SWRisingCapCost
= 0,
Base Cost of New Capacity ,
T CONC ( Time ) )
Units: M$/KWSM
Cost of additional capacity measured in $Million/KWSM. Assumes 1985 average price level of $200 Million for a 20KWSM 6" fab. If WSRisingCapCost is set non-zero, the cost will vary with time.
(000)Time - Internally defined simulation time.
(088)Base Cost of New Capacity - Cost of Capacity in 1985 when a 20KWSM fab cost $200M. (Source TI)
(104)SWRisingCapCost - If SWRisingCapCost = 0, the Cost of New Capacity is a constant, if SWRisingCapCost is non-zero, the Cost fo New Capacity varies by the table function CONC.
(135)T CONC - Cost of adding new capacity in millions of dollars per Kilo 6" equivalent Wafer Start per Month of capacity. Source: Texas Instruments Inc.

(092) Fraction of Revenue to RnD =
IF THEN ELSE ( SWIndustryRnD
= 0,
0,
0.11)
Units: Dimensionless
Percentage of industry revenue devoted to RnD. SWIndustryRnD turns off RnD expenses. If SWIndustryRnD = 0, Fraction of Revenue to RnD = 0.
(103)SWIndustryRnD - If SWIndustryRnD = 0 the R&D effects are turned off, otherwise they are turned on.

(093) Initial Backlog =
Initial Demand
* Target Delivery Delay
* Initial Backlog Inflator
Units: KWS
Initial Backlog of customer orders which have not yet shipped.
(094)Initial Backlog Inflator - Percentage that initial backlog exceeds demand. Estimated from book to bill ratio for years preceeding simulation run.
(097)Initial Demand - Industry wide demand in Thousands of 6" equivalent Wafer Starts per year. Calculated from initial supply adjusted by book to bill ratio
(105)Target Delivery Delay - Target delay between receipt of customer order and shipment product to customer.

(094) Initial Backlog Inflator = 1
Units: Dimensionless
Percentage that initial backlog exceeds demand. Estimated from book to bill ratio for years preceeding simulation run.

(095) Initial Book to Bill = 1.2
Units: Dimensionless
Book to Bill Ratio at the begining of the simulation (from SIA historical data)

(096) Initial Capacity =
Initial Estimated Wafer Supply
/ MPY

Units: KWSM
Industry wide wafer capacity at start of modeling period in thousands of 6" equivalent Wafer Starts per Month
(098)Initial Estimated Wafer Supply - Initail estimated supply of 6" equivalent wafers, from SIA billings data and VLSI Research Inc. silicon demand data.
(100)MPY - Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)

(097) Initial Demand =
Initial Estimated Wafer Supply
* Initial Book to Bill
Units: KWS/yr
Industry wide demand in Thousands of 6" equivalent Wafer Starts per year. Calculated from initial supply adjusted by book to bill ratio
(095)Initial Book to Bill - Book to Bill Ratio at the begining of the simulation (from SIA historical data)
(098)Initial Estimated Wafer Supply - Initail estimated supply of 6" equivalent wafers, from SIA billings data and VLSI Research Inc. silicon demand data.

(098) Initial Estimated Wafer Supply = 12792
Units: KWS/yr
Initail estimated supply of 6" equivalent wafers, from SIA billings data and VLSI Research Inc. silicon demand data.

(099) Initial PP and E =
Initial Capacity
* Cost of New Capacity
Units: M$
Value of Property Plant and Equipment at the begining of the simulation.
(091)Cost of New Capacity - Cost of additional capacity measured in $Million/KWSM. Assumes 1985 average price level of $200 Million for a 20KWSM 6" fab. If WSRisingCapCost is set non-zero, the cost will vary with time.
(096)Initial Capacity - Industry wide wafer capacity at start of modeling period in thousands of 6" equivalent Wafer Starts per Month

(100) MPY = 12
Units: KWS/(yr*KWSM)
Conversion factor to change capacity units (KWSM) into demand units (KWS/yr)

(101) Normal Asset Life = 6.25
Units: yr
Normal depretiation time used to write off capital investments.

(102) Pipeline Factor = 1
Units: Dimensionless
Adjustment factor to capacity contained in pipeline

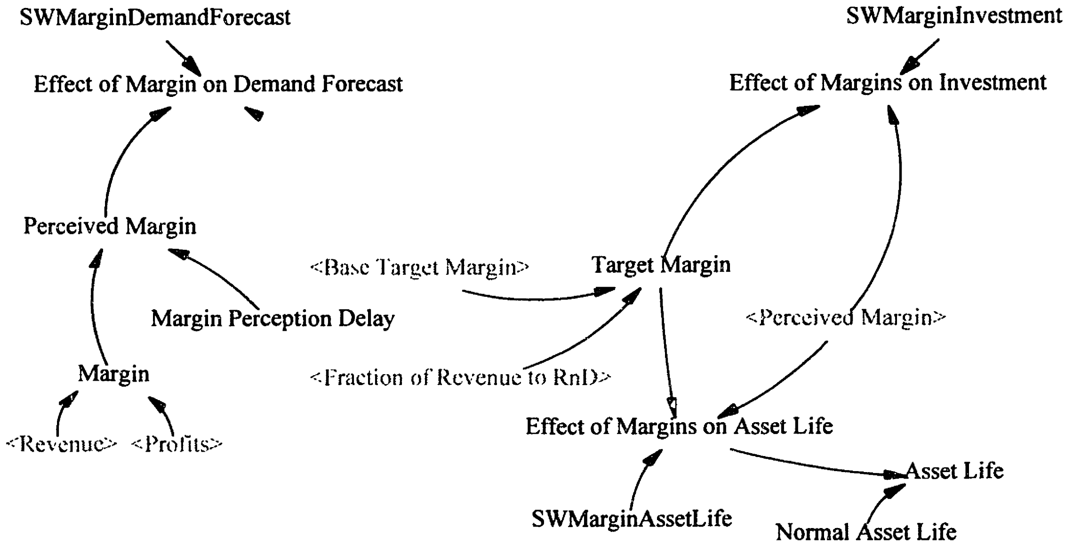
(103) SWIndustryRnD = 0
Units: Dimensionless
If SWIndustryRnD = 0 the R&D effects are turned off, otherwise they are turned on.

(104) SWRisingCapCost = 0
Units: Dimensionless
If SWRisingCapCost = 0, the Cost of New Capacity is a constant, if SWRisingCapCost is non-zero, the Cost fo New Capacity varies by the table function CONC.

(105) Target Delivery Delay = 0.25
Units: yr
Target delay between receipt of customer order and shipment product to customer.

(106) Target Margin =
Base Target Margin
- Fraction of Revenue to RnD
Units: Dimensionless
Desired profit margin based on Intel 1993 net margin.
(089)Base Target Margin - Base Target Margin is the expected profit margin (net margin) without considering R&D expenses.
(092)Fraction of Revenue to RnD - Percentage of industry revenue devoted to RnD. SWIndustryRnD turns off RnD expenses. If SWIndustryRnD = 0, Fraction of Revenue to RnD = 0.

## Margin Effects



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(107) Effect of Margin on Demand Forecast =
IF THEN ELSE ( SWMarginDemandForecast
= 0,
1,
T EMODF ( Perceived Margin
/ Target Margin ) )
Units: Dimensionless
If profits are poor, margin drops below target margin and demand forecasts are discounted. If profits are good, forecasts are inflated.
(112)Perceived Margin - Industry margin as perceived by investment decision makers.
(114)SWMarginDemandForecast - Truns off Effect of Margin on Demand Forecast if SWMarginDemand set to 0.

(106)Target Margin - Desired profit margin based on Intel 1993 net margin.

(141)T EMODF - Effect of Margin on Demand. As profits drop, demand forecasts are discounted. As profits increase demand forecasts are inflated.

(108) Effect of Margins on Asset Life =
IF THEN ELSE ( SWMarginAssetLife
= 0,
1,
T EMOAL ( Perceived Margin
/ Target Margin ) )
Units: Dimensionless
Lookup table for Effect of Margins on Retirements. Input to table is percieved industry profit margin relative to targets.
(112)Perceived Margin - Industry margin as perceived by investment decision makers.
(113)SWMarginAssetLife - Turns on and off the effect of margins on asset life. If SWMarginRetirements = 0, asset life is a constant, otherwise asset life is looked up in a table.
(106)Target Margin - Desired profit margin based on Intel 1993 net margin.
(140)T EMOAL - As margins erode, retirements are slowed initially as productive life of capital equipment is extended. As margins erode farther, retirements are accelerated as companies exit the business.

(109) Effect of Margins on Investment =
IF THEN ELSE ( SWMarginInvestment
= 0,
1,
T EMOI ( Perceived Margin
/ Target Margin ) )
Units: Dimensionless
If perceived margins are above target margins, then more investment will be attracted to the industry. If perceived margins are below target margin then additional investment will be discouraged.
(112)Perceived Margin - Industry margin as perceived by investment decision makers.
(115)SWMarginInvestment - Turns off the effect of margin on prices if SWMarginEffect = 0, Turns on the effect of margin on prices of SWMarginEffect = 1.
(106)Target Margin - Desired profit margin based on Intel 1993 net margin.
(142)T EMOI - Effect of Margins on Investment. If margins are good (>1), investment is attracted to the semiconductor industry from other sources. If margins are poor (<1) new investment is less than desired.

(110) Margin =
ZIDZ ( Profits ,
Revenue )
Units: Dimensionless
Average margin in the semiconductor industry. Somewhere between operating margin and net margin.
(191)Profits - Profits are Revenue minus expenses minus R&D spending
(130)Revenue - Yearly revenue from sale of semiconductor product.

(111) Margin Perception Delay = 1
Units: yr
Time required for improved margins in SC industry to be perceived by investors.

(112) Perceived Margin =
SMOOTH ( Margin ,
Margin Perception Delay )

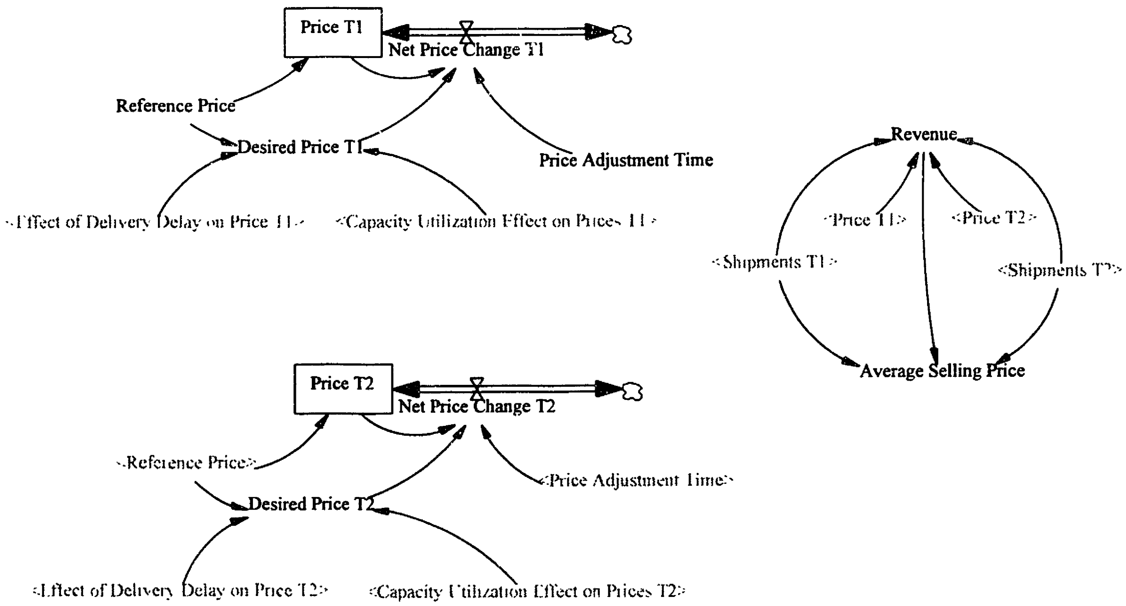
Units: Dimensionless
Industry margin as perceived by investment decision makers.
(110)Margin - Average margin in the semiconductor industry. Somewhere between operating margin and net margin.
(111)Margin Perception Delay - Time required for improved margins in SC industry to be perceived by investors.

(113) SWMarginAssetLife = 0
Units: Dimensionless
Turns on and off the effect of margins on asset life. If SWMarginRetirements = 0, asset life is a constant, otherwise asset life is looked up in a table.

(114) SWMarginDemandForecast = 0
Units: Dimensionless
Truns off Effect of Margin on Demand Forecast if SWMarginDemand set to 0.

(115) SWMarginInvestment = 0
Units: Dimensionless
Turns off the effect of margin on prices if SWMarginEffect = 0, Turns on the effect of margin on prices of SWMarginEffect = 1.

## Pricing and Revenue Sector



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(116) Average Selling Price =
Revenue
/ ( Shipments T1
+ Shipments T2 )
Units: M$/KWS

Average Selling Price of all semiconductor technologies.
(130)Revenue - Yearly revenue from sale of semiconductor product.
(051)Shipments T1 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.
(061)Shipments T2 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

(119) Desired Price T1 =
Reference Price
* Capacity Utilization Effect on Prices T1
* Effect of Delivery Delay on Price T1
Units: M$/KWS
Desired price is price adjusted by utilization effect. SWPriceEffect removes price effect.
(017)Capacity Utilization Effect on Prices T1 - If capacity utilization equals target (implicit target of 100%), CUEOP equals 1. Capacity below target leads to price reductions and capacity above target leads to price increases.
(049)Effect of Delivery Delay on Price T1 - If the actual delivery delay exceeds target, prices rise. If SWDeliveryDelayPrice is set to 0 the effect is set to 1.
(129)Reference Price - Reference price in this model is asumed to be a constant over time. It is measured in Millions of $ per Thousand Wafer Starts

(120) Desired Price T2 =
Reference Price
* Capacity Utilization Effect on Prices T2
* Effect of Delivery Delay on Price T2
Units: M$/KWS
Desired price is price adjusted by utilization effect. SWPriceEffect removes price effect.
(018)Capacity Utilization Effect on Prices T2 - If capacity utilization equals target (implicit target of 100%), CUEOP equals 1. Capacity below target leads to price reductions and capacity above target leads to price increases.
(059)Effect of Delivery Delay on Price T2 - If the actual delivery delay exceeds target, prices rise. If SWDeliveryDelayPrice is set to 0 the effect is set to 1.
(129)Reference Price - Reference price in this model is asumed to be a constant over time. It is measured in Millions of $ per Thousand Wafer Starts

(121) FINAL TIME = 1994
Units: yr
The final time for the simulation.

(123) INITIAL TIME = 1980
Units: yr
The initial time for the simulation.

(124) Net Price Change T1 =
( Desired Price T1
- Price T1 )
/ Price Adjustment Time
Units: M$/(yr*KWS)
Net rate at which prices change, may be positive (price increase) or negative (price decrease)
(127)Price T1 - Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.
(119)Desired Price T1 - Desired price is price adjusted by utilization effect. SWPriceEffect removes price effect.

(126)Price Adjustment Time - Time over which prices are adjusted. A decision to lower price may be implemented, but it takes some time for the new prices to effect the average price because of existing contracts.

(125) Net Price Change T2 =
( Desired Price T2
- Price T2 )
/ Price Adjustment Time
Units: M$/(yr*KWS)
Net rate at which prices change, may be positive (price increase) or negative (price decrease)
(128)Price T2 - Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.
(120)Desired Price T2 - Desired price is price adjusted by utilization effect. SWPriceEffect removes price effect.
(126)Price Adjustment Time - Time over which prices are adjusted. A decision to lower price may be implemented, but it takes some time for the new prices to effect the average price because of existing contracts.

(126) Price Adjustment Time = 0.25
Units: yr
Time over which prices are adjusted. A decision to lower price may be implemented, but it takes some time for the new prices to effect the average price because of existing contracts.

(127) Price T1 =
INTEG( Net Price Change T1 ,
Reference Price )
Units: M$/KWS
Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.
(124)Net Price Change T1 - Net rate at which prices change, may be positive (price increase) or negative (price decrease)
(129)Reference Price - Reference price in this model is asumed to be a constant over time. It is measured in Millions of $ per Thousand Wafer Starts

(128) Price T2 =
INTEG( Net Price Change T2 ,
Reference Price )
Units: M$/KWS
Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.
(125)Net Price Change T2 - Net rate at which prices change, may be positive (price increase) or negative (price decrease)
(129)Reference Price - Reference price in this model is asumed to be a constant over time. It is measured in Millions of $ per Thousand Wafer Starts

(129) Reference Price = 0.848
Units: M$/KWS
Reference price in this model is asumed to be a constant over time. It is measured in Millions of $ per Thousand Wafer Starts

(130) Revenue =
Shipments T1
* Price T1
+ Shipments T2

* Price T2
Units: M$/yr
Yearly revenue from sale of semiconductor product.
(127)Price T1 - Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.
(128)Price T2 - Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.
(051)Shipments T1 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.
(061)Shipments T2 - If SWBacklog is set to 0, SHipments equal Demand, otherwise Shipments are constrained to the lesser of desired shipments and available shipments.

## Table Functions

(131) SAVEPER =
TIME STEP
Units: yr
The frequency with which output is stored.
(153)TIME STEP - The time step for the simulation. in 1/12 year (i.e. months)

(133) T ADJUSTED SIA BOOKINGS (
[(1979,0)-
(1995,100000)],(1979.75,13657),(1980,14372),(1980.25,14663),(1980.5,14149),(1980.75,13435),(1981,12877),(1981.25,12551),(1981.5,12825),(1981.75,13078),(1982,13453),(1982.25,14162),(1982.5,14302),(1982.75,14188),(1983,14739),(1983.25,15910),(1983.5,18642),(1983.75,22648),(1984,25796),(1984.25,28562),(1984.5,29528),(1984.75,27965),(1985,25221),(1985.25,21570),(1985.5,18715),(1985.75,17700),(1986,18886),(1986.25,21263),(1986.5,23592),(1986.75,25645),(1987,27030),(1987.25,28764),(1987.5,31074),(1987.75,33960),(1988,37829),(1988.25,41476),(1988.5,44770),(1988.75,47255),(1989,48628),(1989.25,49366),(1989.5,49004),(1989.75,48562),(1990,48404),(1990.25,48949),(1990.5,50143),(1990.75,51770),(1991,53454),(1991.25,54411),(1991.5,54699),(1991.75,55041),(1992,55173),(1992.25,55706),(1992.5,58507),(1992.75,62015),(1993,66201),(1993.25,71958),(1993.5,77433),(1993.75,81349),(1994,81349) )
Units: M$/yr
SIA Booking Data adjusted to include Japanese Manufacturers prior to 1984.

(134) T Adjusted SIA Sales (
[(1979,0)-
(1995,80000)],(1979.75,10839),(1980,11791),(1980.25,12691),(1980.5,13410),(1980.75,13732),(1981,13947),(1981.25,13896),(1981.5,13807),(1981.75,13844),(1982,13694),(1982.25,13815),(1982.5,13880),(1982.75,13889),(1983,14212),(1983.25,14748),(1983.5,15812),(1983.75,17443),(1984,19442),(1984.25,21855),(1984.5,24197),(1984.75,25954),(1985,26040),(1985.25,24898),(1985.5,23113),(1985.75,21479),(1986,21479),(1986.25,22759),(1986.5,24734),(1986.75,26355),(1987,27637),(1987.25,28867),(1987.5,30189),(1987.75,32530),(1988,35533),(1988.25,38817),(1988.5,41891),(1988.75,45005),(1989,47215),(1989.25,48487),(1989.5,49049),(1989.75,48763),(1990,48169),(1990.25,47929),(1990.5,48954),(1990.75,50519),(1991,52337),(1991.25,53722),(1991.5,54407),(1991.75,54607),(1992,54946),(1992.25,55621),(1992.5,57483),(1992.75,59865),(1993,62767),(1993.25,67503),(1993.5,72593),(1993.75,77310),(1994,77310) )
Units: M$/yr
SIA Sales data adjusted to include Japanese manufacturers prior to 1984

(135) T CONC (
[(1980,0)-(1995,40)],(1980,11.6),(1985,10.3),(1990,20.6),(1993,28.9),(1995,23.2) )
Units: M$/KWSM

Cost of adding new capacity in millions of dollars per Kilo 6" equivalent Wafer Start per Month of capacity. Source: Texas Instruments Inc.

(136) T CUEOP (
[(0,0)-(4,4)],(0,0),(0.25,0.3),(0.5,0.6),(0.75,0.85),(0.85,0.95),(0.95,1),(1,1.02),(1.2,1.05),(2,1.07),(4,1.1) )
Units: Dimensionless
Capacity Utilization Effect on Prices, When capacity utilization is greater than 1, prices rise rapidly, when capacity utilization drops below 1, prices drop toward marginal cost.

(137) T CUEOVC (
[(-1,0)-(3,4)],(-1,0.5),(0,0.5),(0.0721649,0.513158),(0.123711,0.592105),(0.185567,0.710526),(0.278351,0.776316),(0.412371,0.881579),(0.525773,0.960526),(0.7,1),(0.8,1),(0.9,1),(0.95,1.05),(1,1.2),(1.05155,1.28947),(1.12371,1.36842),(1.2268,1.5),(1.47423,1.67105),(1.72165,1.76316),(1.85567,1.84211),(2,2),(3,4) )
Units: Dimensionless
As capacity utilization rises above target of 90% variable costs begin to rise as extra shifts are hired. Capacity utilization below 70% causes firms to reduce labor inputs.

(138) T DPT1VSRnD (
[(0,0)-(2e+010,2)],(0,0.1),(3000,1),(12000,1.1) )
Units: Dimensionless
Density Performance index of technology T1 Vs total R&D spending on the technology.

(139) T DPT2VsRnD (
[(0,0)-(60000,10)],(0,0),(6000,4),(50000,5) )
Units: Dimensionless
Technology index for T2 Vs total R&D spending on T2.

(140) T EMOAL (
[(-1,0)-(3,4)],(-0.5,0.3),(-0.175258,0.447368),(-0.0824742,0.513158),(0,0.6),(0.0824742,0.763158),(0.134021,0.921053),(0.195876,1.15789),(0.278351,1.32895),(0.360825,1.43421),(0.5,1.5),(0.649485,1.48684),(0.752577,1.36842),(0.835052,1.13158),(0.917526,1.02632),(1,1),(1.81443,1),(1.8866,1.03947),(2.02062,1.10526),(2.07217,1.19737),(2.16495,1.28947),(2.30928,1.40789),(2.41237,1.53947),(2.54639,1.65789),(2.97938,2.13158) )
Units: Dimensionless
As margins erode, retirements are slowed initially as productive life of capital equipment is extended. As margins erode farther, retirements are accelerated as companies exit the business.

(141) T EMODF (
[(-4,0)-(4,4)],(-4,0),(1,1),(4,4) )
Units: Dimensionless
Effect of Margin on Demand. As profits drop, demand forecasts are discounted. As profits increase demand forecasts are inflated.

(142) T EMOI (
[(-4,-1)-(4,3)],(-4,-0.1),(-0.25,-0.1),(0,0),(0.125,0.07),(0.25,0.35),(0.4,0.75),(0.65,0.9),(1,1.04),(1.2,1.12),(1.5,1.2),(1.875,1.25),(4,1.3) )
Units: Dimensionless

Effect of Margins on Investment. If margins are good (>1), investment is attracted to the semiconductor industry from other sources. If margins are poor (<1) new investment is less than desired.

(143) T EOCCT1T2 (
[(0,0)-
(10,1)],(0,0),(0.154639,0.269737),(0.360825,0.542763),(0.56701,0.759868),(0.876289,0.973684)
,(1,1),(10,1) )
Units: Dimensionless
As perceived orders for T2 increase as a fraction of total orders, more capacity will be converted to T2

(144) T EPCCT1T2 (
[(0,0)-(10,1)],(0,0),(1,0.1),(10,1) )
Units: Dimensionless
Effect of Performance on Capacity Conversion from T1 to T2. As Relative Performance increases, capacity will be converted in anticipation of user needs.

(145) T EPerfWST1T2 (
[(0,0)-(20,1)],(0,0),(1,0.95),(1.2,0.97),(1.5,0.99),(1.75,0.995),(2.5,1),(10,1) )
Units: Dimensionless
If density and performance of T2 greatly exceeds that of T1, most customers will switch over to T2. If the Density and Performance are relatively equal, most customers will stay with T1.

(146) T EPriWST1T2 (
[(0,0)-
(10,1)],(0,1),(0.283505,0.996711),(0.515464,0.976974),(0.695876,0.957237),(0.876289,0.927632
),(1,0.9),(2,0.1),(2.1134,0.0756579),(2.42268,0.0559211),(2.70619,0.0394737),(3.09278,0.02960
53),(10,0) )
Units: Dimensionless
If T2 is much more expensive than T1, few customers will be willing to switch. If T2 is much less expensive than T1, most customers will be willing to switch.

(147) T PEODG (
[(0,-10)-(10,100)],(0,15),(1,0),(10,-10) )
Units: Dimensionless
Price Effect on Demand Growth - Price sensitivity of demand, normalized. As price drops below 1, demand rises rapidly. As price increases above 1, demand falls off gradually.

(148) T SIA Demand Estimate (
[(1979,0)-
(1995,80000)],(1979.75,12792),(1980.75,15037),(1981.75,16779),(1982.75,17079),(1983.75,225
15),(1984.75,35290),(1985.75,34901),(1986.75,39414),(1987.75,46131),(1988.75,54106),(1989.7
5,57916),(1990.75,63582),(1991.75,66462),(1992.75,66175),(1993.75,72921),(1994,72921) )
Units: KWS/yr
Estimate of yearly 6" equivalent wafer demand per year based on SIA and VLSI Research Inc. data.

(149) T SIA Orders (
[(1980,0)-
(1994,100000)],(1980,8330.65),(1980.25,9219.25),(1980.5,9846.22),(1980.75,9880.55),(1981,98
07.74),(1981.25,9207.76),(1981.5,8764.5),(1981.75,8773.8),(1982,8762),(1982.25,9031.6),(1982.
5,9526.85),(1982.75,9637.25),(1983,9576.84),(1983.25,9774.71),(1983.5,10342.6),(1983.75,119
33.2),(1984,14336.1),(1984.25,19003.5),(1984.5,23714),(1984.75,26897.7),(1985,27964.9),(1985

.25,25220.6),(1985.5,21569.8),(1985.75,18714.8),(1986,17699.8),(1986.25,18885.8),(1986.5,212
63.3),(1986.75,23592.2),(1987,25645.1),(1987.25,27029.6),(1987.5,28764.2),(1987.75,31074.3),(
1988,33960.1),(1988.25,37828.8),(1988.5,41476.4),(1988.75,44770.5),(1989,47255.2),(1989.25,
48628.2),(1989.5,49366.4),(1989.75,49004.4),(1990,48562),(1990.25,48403.8),(1990.5,48948.6),
(1990.75,50143.3),(1991,51770.2),(1991.25,53454.4),(1991.5,54411.3),(1991.75,54698.9),(1992,
55041.5),(1992.25,55173.5),(1992.5,55706.4),(1992.75,58506.9),(1993,62015.2),(1993.25,66200
.7),(1993.5,71957.9),(1993.75,77433.2),(1994,81348.9)
)
Units: M$/yr
SIA Yearly Booking data in $ million of orders per year, summed over last 4 quarters. i.e. data for 1981.00 is yearly orders for 1980.

(150) T SIA Sales (
[(1980,0)-
(1994,80000)],(1980,6611.6),(1980.25,7586.02),(1980.5,8560.51),(1980.75,9415.61),(1981,1002
4.5),(1981.25,9971.38),(1981.5,9724.85),(1981.75,9457.01),(1982,9275.23),(1982.25,9191.54),(1
982.5,9290.79),(1982.75,9351.44),(1983,9374.92),(1983.25,9438.82),(1983.5,9626.38),(1983.75,
10155.4),(1984,11041.6),(1984.25,14386.7),(1984.5,18322.8),(1984.75,22321.8),(1985,25954.2),
(1985.25,26040.2),(1985.5,24898),(1985.75,23112.8),(1986,21479.2),(1986.25,21478.9),(1986.5,
22758.7),(1986.75,24733.9),(1987,26355.4),(1987.25,27637.1),(1987.5,28866.8),(1987.75,30189
.2),(1988,32530.4),(1988.25,35533),(1988.5,38817),(1988.75,41891.2),(1989,45004.8),(1989.25,
47215.5),(1989.5,48487.1),(1989.75,49048.9),(1990,48762.9),(1990.25,48168.7),(1990.5,47928.
7),(1990.75,48954.5),(1991,50518.9),(1991.25,52337.2),(1991.5,53721.5),(1991.75,54407.1),(19
92,54607.4),(1992.25,52534.3),(1992.5,50779.6),(1992.75,50044.3),(1993,49953.9),(1993.25,55
267.1),(1993.5,62433.4),(1993.75,70121.2),(1994,77309.7) )
Units: $/yr
SIA data for total semiconductor sales.

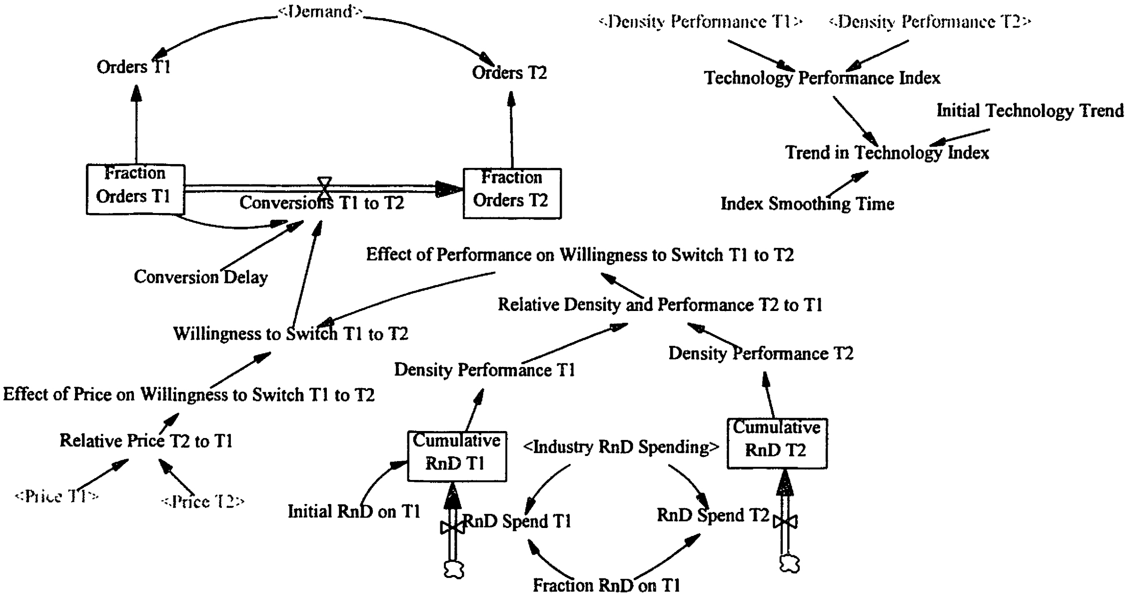
(151) T SIA World Growth (
[(1975,-0.6)-
(2000,0.6)],(1978,0.285),(1979,0.241),(1980,0.272),(1981,0.053),(1982,0.029),(1983,0.261),(198
4,0.464),(1985,-
0.168),(1986,0.239),(1987,0.237),(1988,0.386),(1989,0.073),(1990,0.016),(1991,0.081),(1992,0.0
96),(1993,0.202) )
Units: 1/yr
World semiconductor demand growth, SIA data.

(152) T US GDP Growth (
[(1980,-0.06)-(2000,0.06)],(1980,-0.006),(1980.25,-0.006),(1980.5,-0.006),(1980.75,-
0.006),(1981,0.02),(1981.25,0.02),(1981.5,0.02),(1981.75,0.02),(1982,-0.023),(1982.25,-
0.023),(1982.5,-0.023),(1982.75,-
0.023),(1983,0.033),(1983.25,0.033),(1983.5,0.033),(1983.75,0.033),(1984,0.06),(1984.25,0.06),(
1984.5,0.06),(1984.75,0.06),(1985,0.03),(1985.25,0.03),(1985.5,0.03),(1985.75,0.03),(1986,0.026
),(1986.25,0.026),(1986.5,0.026),(1986.75,0.026),(1987,0.03),(1987.25,0.03),(1987.5,0.03),(1987
.75,0.03),(1988,0.039),(1988.25,0.039),(1988.5,0.039),(1988.75,0.039),(1989,0.026),(1989.25,0.0
26),(1989.5,0.026),(1989.75,0.026),(1990,0.007),(1990.25,0.007),(1990.5,0.007),(1990.75,0.007)
,(1991,-0.013),(1991.25,-0.013),(1991.5,-0.013),(1991.75,-
0.013),(1992,0.0328),(1992.25,0.0328),(1992.5,0.0328),(1992.75,0.0328),(1993,0.0312),(1993.25
,0.0312),(1993.5,0.0312),(1993.75,0.0312),(1994,0.0449) )
Units: 1/yr
Average annual GDP Growth for US.

(153) TIME STEP = 0.25
Units: yr

The time step for the simulation. in 1/12 year (i.e. months)

## Technology Sector



**********************************

.Technology

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(154) Conversion Delay = 1
Units: yr
Length of time it takes customers to convert from T1 to T2. Conversion will require design of new products or redesign of existing products.

(155) Conversions T1 to T2 =
Fraction Orders T1
* Willingness to Switch T1 to T2
/ Conversion Delay
Units: Fraction/yr
Rate at which orders convert from technology T1 to technology T2
(162)Fraction Orders T1 - Assumes that simulation starts with T1 the only technology available.
(154)Conversion Delay - Length of time it takes customers to convert from T1 to T2. Conversion will require design of new products or redesign of existing products.
(176)Willingness to Switch T1 to T2 - An index of how willing customers are to switch from T1 to T2. If Willingness = 0, customers will stay with T1, if willingness >0, customers will begin to move to T2

(156) Cumulative RnD T1 =
INTEG( RnD Spend T1 ,
Initial RnD on T1 )
Units: M$
Ammount of R&D spent on developing technology T1. T1 is assumed to be the dominant technology at the begining of the simulation.
(166)Initial RnD on T1 - The amount of R&D spent on technology T1 at the start of the simulation.

(172)RnD Spend T1 - Amount of R&D spent on developent technology T1.

(157) Cumulative RnD T2 =
INTEG( RnD Spend T2 ,
0)
Units: M$
Cumulative amount spent on R&D for technology T2. Assumed to be zero at the begining of the simulation.
(173)RnD Spend T2 - Amount of R&D spent on T2 each year

(158) Density Performance T1 =
T DPT1VSRnD ( Cumulative RnD T1 )
Units: Dimensionless
Index of Density and Performance for technology T1. Determined by table function.
(156)Cumulative RnD T1 - Ammount of R&D spent on developing technology T1. T1 is assumed to be the dominant technology at the begining of the simulation.
(138)T DPT1VSRnD - Density Performance index of technology T1 Vs total R&D spending on the technology.

(159) Density Performance T2 =
T DPT2VsRnD ( Cumulative RnD T2 )
Units: Dimensionless
Denasity Performance index of technology T2, generated by a table function
(157)Cumulative RnD T2 - Cumulative amount spent on R&D for technology T2. Assumed to be zero at the begining of the simulation.
(139)T DPT2VsRnD - Technology index for T2 Vs total R&D spending on T2.

(160) Effect of Performance on Willingness to Switch T1 to T2 =
T EPerfWST1T2 ( Relative Density and Performance T2 to T1 )
Units: Dimensionless
If density and performance of T2 greatly exceeds that of T1, most customers will switch over to T2. If the Density and Performance are relatively equal, most customers will stay with T1.
(170)Relative Density and Performance T2 to T1 - Ratio of the density performance index of T2 to that of T1. A measure of how much better T2 is than T1.
(145)T EPerfWST1T2 - If density and performance of T2 greatly exceeds that of T1, most customers will switch over to T2. If the Density and Performance are relatively equal, most customers will stay with T1.

(161) Effect of Price on Willingness to Switch T1 to T2 =
T EPriWST1T2 ( Relative Price T2 to T1 )
Units: Dimensionless
Effect of Price on Willingness to Switch is determined by table function EPWST1T2
(171)Relative Price T2 to T1 - Ratio of price for T1 to price for T2. Prices are wafer prices for T1 and T2
(146)T EPriWST1T2 - If T2 is much more expensive than T1, few customers will be willing to switch. If T2 is much less expensive than T1, most customers will be willing to switch.

(162) Fraction Orders T1 =
INTEG( - Conversions T1 to T2 ,
1)
Units: Fraction
Assumes that simulation starts with T1 the only technology available.
(155)Conversions T1 to T2 - Rate at which orders convert from technology T1 to technology T2

(163) Fraction Orders T2 =
INTEG( Conversions T1 to T2 ,
0)
Units: Fraction
Fraction of orders for technology T2, assumed to be 0 at begining of simulation.
(155)Conversions T1 to T2 - Rate at which orders convert from technology T1 to technology T2

(164) Fraction RnD on T1 =
1
- RAMP ( 0.666667,
1980.5,
1982)
Units: Dimensionless
The conversion of R & D spending from T1 to T2 is hardwired to take place between mid 1980 and 1982

(165) Index Smoothing Time = 0.25
Units: yr
Time over which technology trend is averaged.

(166) Initial RnD on T1 = 2500
Units: M$
The amount of R&D spent on technology T1 at the start of the simulation.

(167) Initial Technology Trend = 0
Units: Dimensionless/yr
Initial value of technology trend at begining of simulation.

(168) Orders T1 =
Demand
* Fraction Orders T1
Units: KWS/yr
Orders for Technology T1 as a fraction of industry orders.
(184)Demand - Yearly Industry wide demand for silicon product in Thousands of 6" equivalent Wafer Starts.
(162)Fraction Orders T1 - Assumes that simulation starts with T1 the only technology available.

(169) Orders T2 =
Demand
* Fraction Orders T2
Units: KWS/yr
Orders for technology T2 as a fraction of industry orders
(184)Demand - Yearly Industry wide demand for silicon product in Thousands of 6" equivalent Wafer Starts.
(163)Fraction Orders T2 - Fraction of orders for technology T2, assumed to be 0 at begining of simulation.

(170) Relative Density and Performance T2 to T1 =
Density Performance T2
/ Density Performance T1
Units: Dimensionless
Ratio of the density performance index of T2 to that of T1. A measure of how much better T2 is than T1.

(158)Density Performance T1 - Index of Density and Performance for technology T1. Determined by table function.
(159)Density Performance T2 - Denasity Performance index of technology T2, generated by a table function

(171) Relative Price T2 to T1 =
XIDZ ( Price T2 ,
Price T1 ,
1)
Units: Dimensionless
Ratio of price for T1 to price for T2. Prices are wafer prices for T1 and T2
(127)Price T1 - Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.
(128)Price T2 - Average price of semiconductor product measured in $Million/KWS. This is equivalent to the revenue per thousand wafers.

(172) RnD Spend T1 =
Industry RnD Spending
* Fraction RnD on T1
Units: M$/yr
Amount of R&D spent on developent technology T1.
(164)Fraction RnD on T1 - The conversion of R & D spending from T1 to T2 is hardwired to take place between 1983 and 1986
(190)Industry RnD Spending - Amount of industry revenues spent on process R&D.

(173) RnD Spend T2 =
Industry RnD Spending
* ( 1
\- Fraction RnD on T1 )
Units: M$/yr
Amount of R&D spent on T2 each year
(164)Fraction RnD on T1 - The conversion of R & D spending from T1 to T2 is hardwired to take place between 1983 and 1986
(190)Industry RnD Spending - Amount of industry revenues spent on process R&D.

(174) Technology Performance Index =
MAX ( Density Performance T1 ,
Density Performance T2 )
Units: Dimensionless
Overall technology index represents the maximum density/performance that can be achieved by any technology at a given point in time.
(158)Density Performance T1 - Index of Density and Performance for technology T1. Determined by table function.
(159)Density Performance T2 - Denasity Performance index of technology T2, generated by a table function

(175) Trend in Technology Index =
TREND ( Technology Performance Index ,
Index Smoothing Time ,
Initial Technology Trend )
Units: Dimensionless/yr
Growth rate in technology averaged over the Index Smoothing Time.
(165)Index Smoothing Time - Time over which technology trend is averaged.
(167)Initial Technology Trend - Initial value of technology trend at begining of simulation.

(174)Technology Performance Index - Overall technology index represents the maximum density/performance that can be achieved by any technology at a given point in time.

(176) Willingness to Switch T1 to T2 =
Effect of Performance on Willingness to Switch T1 to T2
* Effect of Price on Willingness to Switch T1 to T2
Units: Dimensionless
An index of how willing customers are to switch from T1 to T2. If Willingness = 0, customers will stay with T1, if willingness >0, customers will begin to move to T2
(160)Effect of Performance on Willingness to Switch T1 to T2 - If density and performance of T2 greatly exceeds that of T1, most customers will switch over to T2. If the Density and Performance are relatively equal, most customers will stay with T1.
(161)Effect of Price on Willingness to Switch T1 to T2 - Effect of Price on Willingness to Switch is determined by table function EPWST1T2

## Macro Functions

```
(196)   :MACRO: TREND ( in ,at ,ini )
TREND  =
      ZIDZ ( in
            - avval ,
          at
            * avval )
    ~ 1/at
    ~     |
avval  =
      INTEG( ( in
            - avval )
            / at ,
          in
            / ( 1
                + ini
                   * at ) )
    ~ in
    ~     |
:END OF MACRO:

          [0,0]


(117)   :MACRO: DELAY3 ( IN ,DEL )
        DELAY3  =
    LV3
       / DL
            ~ IN
            ~     |
LV3  =
     INTEG( RT2
           - DELAY3 ,
        DL
           * IN )
```

```
    ~ IN*DEL
    ~     |
DL =
      DEL
         / 3
    ~ DEL
    ~     |
RT2 =
      LV2
         / DL
    ~ IN
    ~     |
LV2 =
      INTEG( RT1
             - RT2 ,
         LV3 )
    ~ IN*DEL
    ~     |
RT1 =
      LV1
         / DL
    ~ IN
    ~     |
LV1 =
      INTEG( IN
             - RT1 ,
         LV3 )
    ~ IN*DEL
    ~     |
:END OF MACRO:

         [0,0]


(118)   :MACRO: DELAY3I ( IN ,DEL ,INI )
DELAY3I =
      LV3
         / DL
    ~ IN
    ~     |
LV3 =
      INTEG( RT2
             - DELAY3I ,
         INI
            * DL )
    ~ IN*DEL
    ~     |
DL =
      DEL
```

```
          / 3
    ~ DEL
    ~     |
RT2 =
      LV2
          / DL
    ~ IN
    ~     |
LV2 =
      INTEG( RT1
              - RT2 ,
          LV3 )
    ~ IN*DEL
    ~     |
RT1 =
      LV1
          / DL
    ~ IN
    ~     |
LV1 =
      INTEG( IN
              - RT1 ,
          LV3 )
    ~ IN*DEL
    ~     |
:END OF MACRO:

          [0,0]


(122)   :MACRO: FORECAST ( in ,at ,hor )
FORECAST =
      in
          * ( 1
              + trd
                  * hor )
    ~ in
    ~     |
trd =
      ZIDZ ( in
              - av ,
          at
              * av )
    ~ 1/at
    ~     |
av =
      INTEG( ( in
              - av )
              / at ,
```

```
        in )
    ~ in
    ~     |
:END OF MACRO:

          [0,0]


(132)   :MACRO: SMOOTH ( IN ,ST )
SMOOTH  =
     INTEG( ( IN
            - SMOOTH )
            / ST ,
        IN )
    ~ IN
    ~     |
:END OF MACRO:

          [0,0]


(196)   :MACRO: TREND ( in ,at ,ini )
TREND  =
     ZIDZ ( in
            - avval ,
        at
            * avval )
    ~ 1/at
    ~     |
avval  =
     INTEG( ( in
            - avval )
            / at ,
        in
            / ( 1
                + ini
                    * at ) )
    ~ in
    ~     |
:END OF MACRO:

          [0,0]

(117)   :MACRO: DELAY3 ( IN ,DEL )
DELAY3  =
     LV3
        / DL
    ~ IN
    ~     |
```

```
LV3 =
      INTEG( RT2
              - DELAY3 ,
          DL
              * IN )
    ~ IN*DEL
    ~     |
DL =
      DEL
          / 3
    ~ DEL
    ~     |
RT2 =
      LV2
          / DL
    ~ IN
    ~     |
LV2 =
      INTEG( RT1
              - RT2 ,
          LV3 )
    ~ IN*DEL
    ~     |
RT1 =
      LV1
          / DL
    ~ IN
    ~     |
LV1 =
      INTEG( IN
              - RT1 ,
          LV3 )
    ~ IN*DEL
    ~     |
:END OF MACRO:

          [0,0]


(118)   :MACRO: DELAY3I ( IN ,DEL ,INI )
DELAY3I =
      LV3
          / DL
    ~ IN
    ~     |
LV3 =
      INTEG( RT2
              - DELAY3I ,
          INI
```

```
            * DL )
    ~ IN*DEL
    ~     |
DL  =
        DEL
           / 3
    ~ DEL
    ~     |
RT2  =
        LV2
           / DL
    ~ IN
    ~     |
LV2  =
        INTEG( RT1
              - RT2 ,
           LV3 )
    ~ IN*DEL
    ~     |
RT1  =
        LV1
           / DL
    ~ IN
    ~     |
LV1  =
        INTEG( IN
              - RT1 ,
           LV3 )
    ~ IN*DEL
    ~     |
:END OF MACRO:

         [0,0]


(122)   :MACRO: FORECAST ( in ,at ,hor )
FORECAST  =
        in
           * ( 1
              + trd
                 * hor )
    ~ in
    ~     |
trd  =
        ZIDZ ( in
              - av ,
           at
              * av )
    ~ 1/at
```

```
    ~     |
av =
      INTEG( ( in
              - av )
              / at ,
          in )
    ~ in
    ~     |
:END OF MACRO:

          [0,0]

(132)   :MACRO: SMOOTH ( IN ,ST )
SMOOTH  =
      INTEG( ( IN
              - SMOOTH )
              / ST ,
          IN )
    ~ IN
    ~     |
:END OF MACRO:

          [0,0]
```

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