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Not with a bang, but with a whimper: Understanding delays in semiconductor supply chain dynamics

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ABSTRACT

The semiconductor industry is characterized by high volatility: rapid increases in market demand are followed by sharp downturns. Therefore, one would expect its supply chains to be very fast in adjusting to changes in demand. However, empirical data from one leading semiconductor firm suggest that delays in adjusting to the latest downturn of the market in 2001 have been considerable. For instance, inventory levels have taken two years to come back in line. Generally, these delays and the dynamics that are causing them are not well understood within the industry.

This paper presents research that explains these delays by means of a system dynamics simulation model that captures the overall supply chain structure, the generic decision-making processes and the associated supply chain dynamics typical for this industry. The model is based upon pre-existing and well-tested generic supply chain models from the literature. It has been tailored and validated with representatives from a major European IC manufacturer. Its dynamic performance has been calibrated using four years of data on key performance aspects such as inventory levels, cycle times, demand flexibility and delivery quality.

With this model, several SCM policies are explored that are effective in improving both sales and supply chain performance, such as more aggressive capacity build-up, lower capacity utilization targets and higher end product buffer stocks.

Not with a bang, but with a whimper: Understanding delays in semiconductor supply chain dynamics

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This is the way the world ends
This is the way the world ends
This is the way the world ends
Not with a bang but with a whimper.
[From T.S. Elliot, The Hollow Men]

Introduction

The semiconductor industry is characterised by high volatility: long-term market growth rates have been impressive, but demand can go up and down substantially from one year to another. For instance, from 1998 to 2000, semiconductor industry sales rose more than 35%, only to go down almost just as much from 2000 to 2002 (WSTS 2003). This is a "high-clockspeed" industry (Fine 1998), where rates of innovation are high, product life cycles are short and new products are pushed out into the market as fast as possible.

In such an industry, one would expect the supply chains that are responsible for the production and distribution of IC's to be very fast in adjusting to variations in demand. One would expect major shocks to the supply chain to be absorbed "with a bang, not with a whimper". Also, one would expect delays in responding to changes to be under close scrutiny of company management and, overall, fairly well understood. Interestingly, our dealings with managers in a variety of firms in this industry (Akkermans et al. 1999, Akkermans 2001, Akkermans and van der Horst 2002, Akkermans et al. 2003) suggest that neither expectation is correct. Delays in responding to demand variability *can* be very substantial, in some cases several years. Here, the response to a shock to the supply chain indeed ends "not with a bang, but with a whimper". Also, the extent of these delays is usually not well recognised. Moreover, what is driving them is generally not well understood.

This then becomes the goal of this paper: to shed more light on delays in adjusting supply chain performance to variations in market demand, on root causes for these delays and on policies for improving supply chain performance in view of this. For this purpose, we present a generic system dynamics simulation model that captures the overall supply chain structure, generic decision-making processes and associated supply chain dynamics typical for the semiconductor industry. We show how we have validated and calibrated this model with representatives and quantitative data from one leading European IC manufacturer.

We take advantage of the unprecedented IC market demand peak of 2001 and the subsequent period of demand stability and use it as a unique real-world "test signal" in four years of time series data on key performance indicators. On the basis of our analysis, we suggest that there are three different types of delays in response of supply chain performance, which we have labelled as operational, tactical and strategic. We identify policies to dramatically improve supply chain performance at each of this levels, based on policy experiments with our generic simulation model.

2. Literature review

Delays in reacting to variations in market demand for different aspects of supply chain performance have long been studied. The seminal works here are those of Forrester (1958, 1961), who investigated the effect of changes in market demand on a four-level supply chain. Forrester incorporated delays in both the physical structure of his supply chain as in the managers' decisions and policies governing inventory adjustment. Forrester found that these delays were responsible for much of the oscillatory behaviour of many supply chains. He found that the nature of the managerial policies concerned could modify these delays and the resulting instabilities of supply chains considerable. His model was later on converted into the well-known "Beer Game" (Sterman 1989), in which these policies and delays generate well-known supply chain dynamics such as the Bull-whip effect (Lee et al. 1997a,1997b, Fransoo and Wouters 2000).

In the field of system dynamics, this work has been followed up by several other authors over the years, such as Mass (1975) who investigated the interactions between inventory-production policies and Morecroft (1983) who looked at the impact of implementing Material Requirements Planning (MRP) systems on supply chain performance.

In the world of supply chain management, these supply chain dynamics insights were taken up in Europe from the late nineteen seventies onwards (van Aken 1978, Hoekstra and Romme 1991, Evans et al. 1993). In the last decade however, in US mainstream OR research interest in the impact of delays on supply chain performance has risen considerably. There is Lee et al.'s (1997a, 1997b) publication on the bull-whip effect of upstream demand amplification in the supply chain. Baganha and Cohen (1998) look at the stabilising effect of inventory on supply chain performance. Chen (1999) considers at the impact of information delays on decentralised supply chains, Cachon (1999) investigated the relation between demand variability and ordering policies. Chen et al. (2000) explore the impact of forecasting, lead times and information sharing on the bullwhip effect in a simple supply chain.

Recently, there is a renewed stream of publications from the field of system dynamics proper on the nature of delays in supply chains. Anderson et al. (2000) look at upstream supply chain volatility in the machine tool industry. Anderson and Morrice (2000) describe a teaching game in a service supply chain. Berends and Romme (2001) look at cyclicality in the paper industry and Akkermans and Vos (2003) at demand amplification in a service supply chain. Gonçalvez (2002) has recently completed ongoing research on the semiconductor supply chain at Intel, to which the current paper is closely linked.

3. Research method

Selection of research design

The research reported here combines a simulation modelling research design with case study research. As the topic of this paper is the nature of delays in responding to demand changes in semiconductor supply chains, and as this topic appears to be not well understood, exploratory, theory-building research was required. In general, research of this type has been found to be underrepresented in POM research (Flynn et al. 1990, Meredith 1993, Neely 1993). Case studies are often employed for exploratory, theory-building research (Yin 1989, Eisenhardt 1989, Meredith 1993).

But, given the specific nature of the issue at hand, simulation modelling seems equally relevant as a research approach. A central premise of this paper is that the main reason why delays in system supply chain response are not well understood is the dynamic nature of the phenomenon (c.f. Repenning 2002). It is generally accepted in the literature that the ways in which supply chains deal with variations in market demand is an inherently dynamic process, in which numerous variables interconnected in multiple feedback processes play a part. Unfortunately, human ability to reliably infer the behaviour of even low-order dynamic systems is exceedingly limited (c.f. Sterman 1989). So, we present in this paper a simulation model whose variables and linkages in themselves are mostly well-documented in the literature (mainly Forrester 1968, Sterman 2000, Hopp and Spearman 2000) but whose interactions in this specific context are not well understood.

Selection of case setting

Our selection criteria for the company to be studied were driven by our research questions (Yin 1989, Eisenhardt 1989, Meredith 1993). This implies that we needed a real-world semiconductor supply chain where:

a) a clear pattern of demand variability had been observed;
b) supply chain performance was significantly affected by this pattern in different respects;
c) sufficient time series and other quantitative data were available to trace this behaviour over time and calibrate the model to this particular real-world setting;
d) knowledgeable company representatives were willing and able to provide input to the modelling process and validate the overall structure and dynamics of the model.

The dramatic boom-and-bust cycle of 1999-2001, with 2001 being the "worst year ever" in the semiconductor industry provided an ideal opportunity for the first requirement. As Figure 1 shows, here demand rose spectacularly in 1999, only to drop equally dramatically from late 2000 onwards. Since this drop, the market has been relatively stable. This comes as close to giving a major "test signal input" to a real-world system as one is ever likely to get. The Semiconductor Company whose empirical data we present here in our case study is where the first author conducted his Master thesis research (Bezemer 2003). In this company, knowledgeable SCM professionals and managers were willing to share their insights with him in a series of interviews and group model-building workshops (Akkermans 1995, Vennix 1996, Akkermans and Vennix 1997). Also, four years of time series data on key aspects of supply chain performance could be distilled from company records.

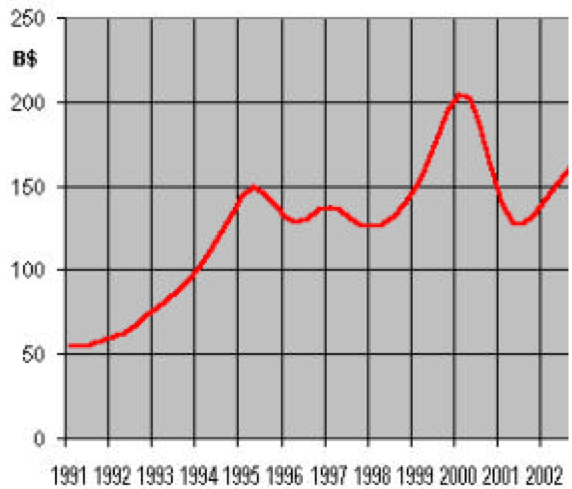


Figure 1: The semiconductor boom-and-bust cycle of 1998-2001, from WSTS (2003)

Research model and research questions
Our conceptual research model is visualised in Figure 2. First of all, this figure illustrates that we look at different aspects of supply chain performance: quality, cost, time and flexibility. These four generic categories are normally used to assess supply chain performance in particular and business process performance in general (c.f. Neely et al. 1995, Neely 1998).

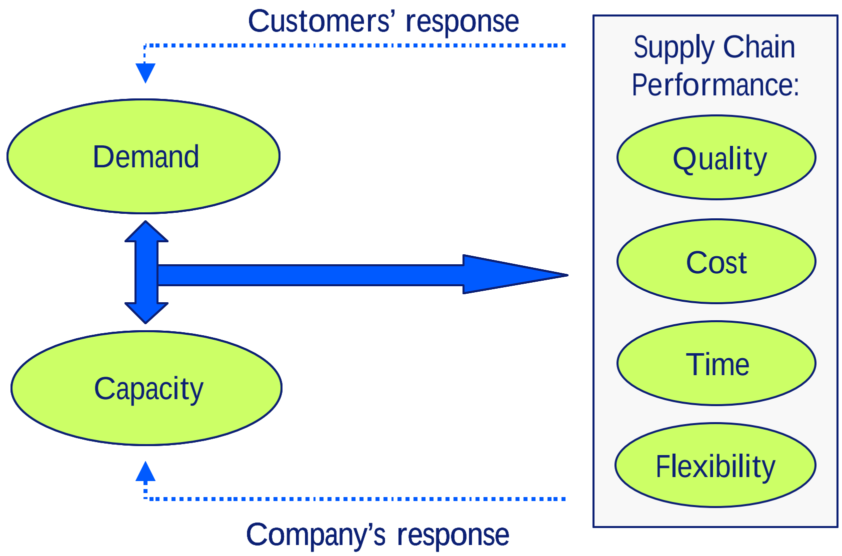


Figure 2: Conceptual research model of drivers of supply chain performance

A central finding from the literature on supply chain management is that the match of demand versus supply is key in determining supply chain performance. The more demand nears maximal capacity, the more supply chain performance suffers: lead times become longer, costs in terms of inventories increase, quality drops and further flexibility is reduced. As demand drops, *over time* performance will recover. This leads to our first research question:

> *Q1: If demand is quickly raised to exceed capacity, and then brought down again, what are the delays in responding to this variability in demand in terms for supply chain performance in terms of cost, quality, time and flexibility?*

As we will see, different supply chain performance indicators have very different adjustment delays for their performance. Some take several years to come back in line, others return quickly back to normal. Why is that? This leads to our second research question in this paper:

> *Q2: If there are differences between the adjustment delays for different aspects of supply chain performance, how can these be explained?*

Finally, were are interested in more than just understanding why supply chain performance does not recover quickly, we want to improve supply chain performance. Hence, our third research question becomes:

> *Q3: What managerial policies can reduce the degree in which supply chain performance suffers as a result of major variations in market demand, and hence reduce the adjustment delays for each of the key SC performance aspects?*

4. Supply chain model

The supply chain model that was developed for this research was triggered by group model-building workshops with SCM experts from the semiconductor company studied. Nevertheless, its formal structure is strongly based upon the existing literature. As shown in Figure 3, this model consists of the following interacting sectors:

1. *Goods flow*: production and shipment of products
2. *Order flow*: order acceptance and order fulfilment
3. *Customer demand*: generation of forecasts and actual order rate
4. *Capacity management*: adjustment of available capacity

The overall structure of interactions between goods flow and order flow is based upon Chapter 18 of Sterman (2000). The throughput and cycle-time calculation formulae come from Hopp and Spearman's *Factory Physics* (2000). The interactions with customer demand and changes in capacity are drawn from Forrester's (1968) market growth model.

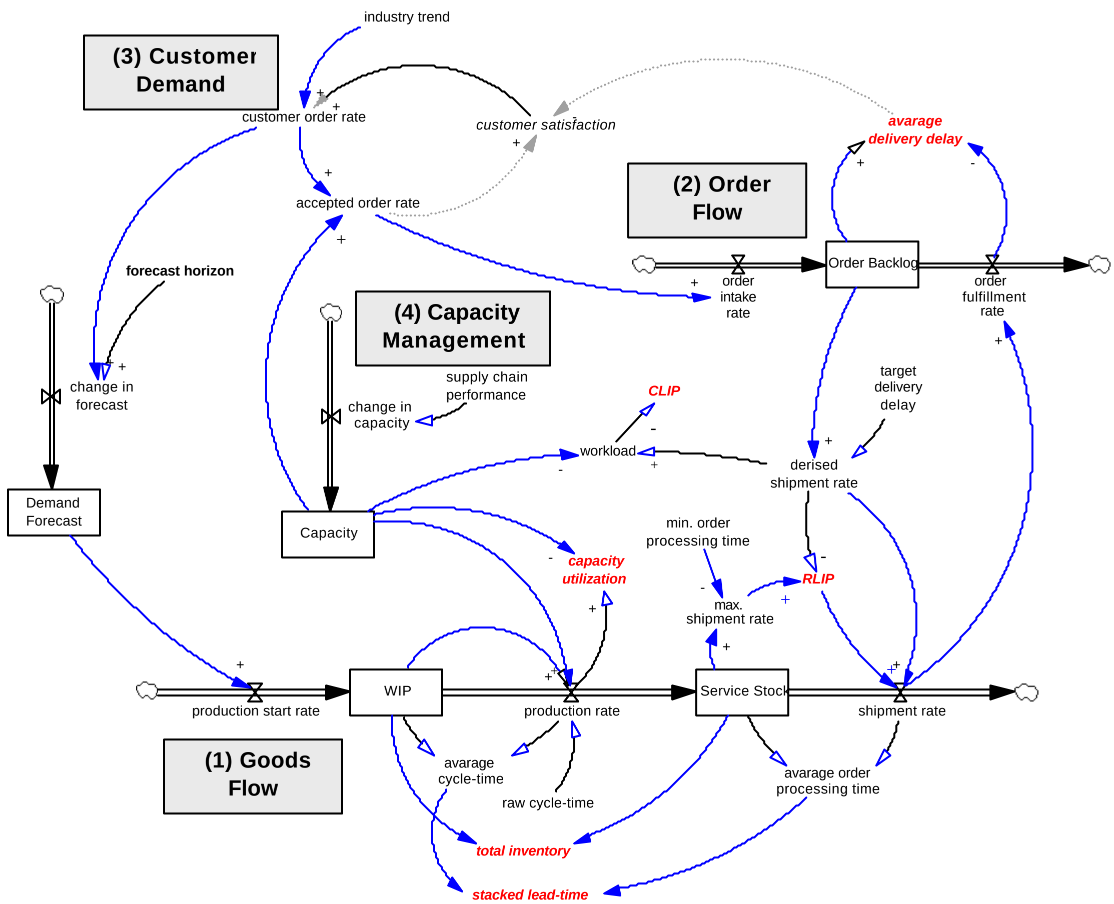


Figure 3: Simplified stocks-and-flow diagram of supply chain model structure

Goods flow

The goods flow is split up into two stages. These stages are separated by the die-bank, which is the Customer Order Decoupling Point (CODP) (Hoekstra and Romme 1991) most commonly used in the semiconductor industry. Production control and inventory management decisions made by the company are endogenous. With respect to this, the production system is organized as an hybrid push-pull production system (Hodgson and Wang 1991a, 1991b; Spearman and Zazanis 1992). It combines a push system at the upstream stage (WIP) and a pull system at the downstream stage (Service Stock).

There is only limited capacity available for production. On one hand, this sets the theoretical maximum production rate. As with a simple production line, it is not possible to make more products than the bottleneck allows for. On the other hand, cycle-times are dependent on the realized capacity utilization. It is found that higher levels of capacity utilization result into longer queue-times (Hopp and Spearman 2000).

A distinction is made between raw cycle-time and queue-time. Raw cycle-time is mainly influenced by aspects like process-technology and product-design and is therefore considered to be exogenous. However, queue-time is endogenous. For calculating queue-time, the production system is modelled according to the "practical worst case", in which maximum randomness is assumed (Hopp and Spearman 2000). Infinite WIP is necessary to fully use the bottleneck capacity. As a result, queue-times explode for high levels of capacity utilization (Figure 4). Details about the model structure are given in Appendix 1.

- Raw Cycle Time (T_0): average time it takes a single job to traverse an empty line
- Bottleneck Rate (r_b): rate of the process center having the least long-term capacity
- Critical WIP (W_0) is

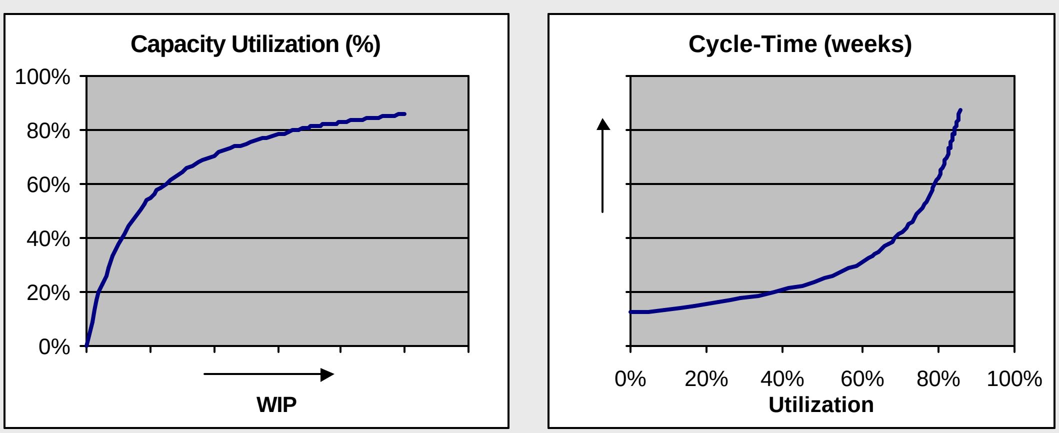
$$W_0 = T_0 r_b$$

- Practical Worst Case cycle-time for a given WIP-level, w, is

$$CT_{pwc} = T_0 + \frac{w-1}{r_b}$$

- Practical Worst Case throughput for a given WIP-level, w is

$$TH_{pwc} = \frac{w}{W_0 + w - 1} r_b$$



Available capacity and raw cycle-time are constant

Figure 4: Key "Factory Physics" for cycle-time and WIP levels (Hopp and Spearman 2000)

Order flow

In contrast to the upstream stage, the downstream stage, i.e. assembly and distribution, operates as a pull system, with shipments based on current demand signals. In order to prevent the system from overflowing, order acceptance is limited to the capacity available for production. When accepted, endogenous order fulfilment determines the adequacy of the inventory available at the service stock.

In order to account for the processes carried out downstream of the die-bank, an exogenous minimum order processing time is defined. As orders cannot be shipped instantly, customers allow for a delivery delay. All unfilled orders remain in a backlog. It is assumed that, once orders are in the order backlog they cannot be changed or cancelled. Details about the model structure are given in Appendix 2.

Customer demand

As show in Figure 3, customer demand is endogenous. It is modelled as a function of both an industry trend and customer satisfaction. The industry trend is exogenous and determines the base volume and some external variability. However, customer demand is endogenous, since it is determined by the delivery performance perceived by the customer.

Delivery performance is basically determined by product availability. Any incoming orders need to be accepted first. Accepted orders state the desired shipments to be made in terms of time and volume. In the simulation model it is assumed that orders can only be shipped once they are complete. Through taking volume for granted, shipment gaps are only related to on-time delivery. Consequently, delivery performance can be modelled as a function of order acceptance and on-time delivery. Details about the model structure are given in Appendix 3.

- *Customer Order Rate = Industry Trend * Customer Satisfaction*
- *Customer Satisfaction = f (Order acceptance, On-time delivery)*

Capacity management

In Figure 3 it is pointed out that pressure to change capacity arises as a result of the perceived supply chain performance. In the model, a distinction is made between available capacity and desired capacity. The desired capacity is influenced by delivery performance (order acceptance and on-time delivery) and capacity utilization. After a delay, actual capacity will be aligned with the desired capacity. Details about the model structure are given in Appendix 4.

- *Capacity = f (Desired Capacity, Capacity acquisition delay)*
- *Desired Capacity = f (Order acceptance, On-time delivery, Capacity utilization)*

Key performance indicators

For tracking the system's performance, six key performance indicators are identified in Figure 3 (shown in red italics). These are in line with the generic categories found for assessing supply chain performance (c.f. Neely et al. 1995, Neely 1998).

- The supply chain delivery quality is reflected in the CLIP, or "confirmed line item performance". This is an industry-specific term for measuring delivery quality, meaning the percentage of order elements that was delivered as promised. The equivalent used in the model, is directly related to the workload. It is defined as a non-linear function (f_1) of capacity and desired shipments.

$$CLIP = f_1\left(\frac{Capacity}{Desired\ Shipment\ Rate}\right)$$

- The supply chain cost are reflected in the total on-hand inventory and capacity utilisation. The total inventory is defined as the sum of WIP and service stock. The capacity utilization is the ration of the actual production rate and the available capacity.

$$Inventory = WIP + Service\ Stock$$

$$Capacity\ Utilisatio\ n = \frac{Prodcution\ Rate}{Capacity}$$

- The supply chain delivery timeliness are reflected in the stacked lead-time and the delivery delay. The former meaning the total time necessary for production and distribution. The latter meaning the number of weeks between order acceptance and actual delivery at the customer. Both measures are derived using Little's Law:, which provide a fundamental relation between WIP, cycle-time and throughput.

$$Stacked\ Lead\ Time = \frac{WIP}{Production\ Rate} + \frac{Service\ Stock}{Shipment\ Rate}$$

$$Average\ Delivery\ Delay = \frac{Order\ Backlog}{Order\ Fulfillmen\ t\ Rate}$$

- The supply chain delivery flexibility is reflected in the RLIP, or "requested line item performance". This an industry-specific term for the degree in which market demands could be met, measured as the percentage of order elements requested by customers that are confirmed by the company. The equivalent used in the model, is defined as a non-linear function (f_2) of the maximum shipment rate and the desired shipment rate.

$$RLIP = f_2\left(\frac{Maximum\ Shipment\ Rate}{Desired\ Shipment\ Rate}\right)$$

5. Case Setting

Case company profile
For production and distribution, a standard supply chain structure is used (Figure 5). Technologically speaking, the most complex production process is diffusion (Diff). This is the longest step in the total production process, and the most costly one. With a series of steps pieces of silicon are transformed into a set of wafers containing numerous ICs. The wafers produced are tested (WT) and put on stock (Die Bank). In response to customer demand, the ICs are cut from the wafer, assembled (Assy) and tested once more (FT). They are moved to an industrial warehouse (IWH) and from there either to a regional distribution centre (RDC) or directly to one of the major customers within the context of a specific customer program.

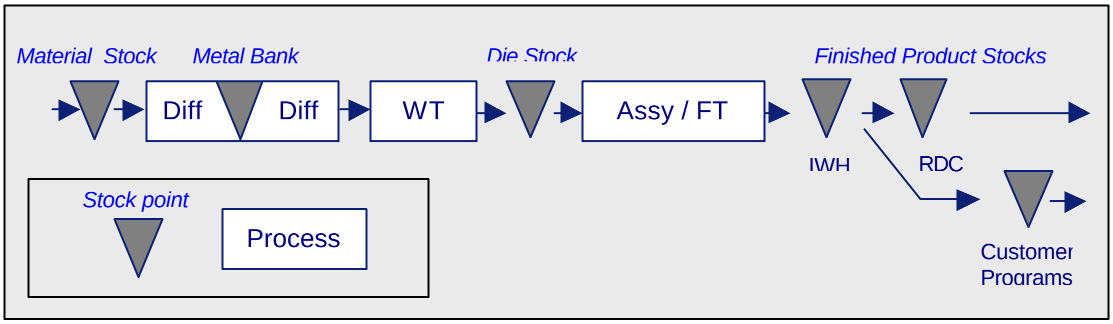


Figure 5: Semiconductor manufacturing supply chain structure

Semiconductor industry trends
The market and supply chain setting this case company was in is typical for its industry. One list of key trends in this major industry is the following:

- *Rapidly changing technologies*: In general, the semiconductor industry can be characterised by a relatively high rate of change in products, processes, technologies, and organisational structures (Fine, 1998). Great advances in IC-design and process technology have triggered this rate of change over the last two decades. This industry has witnessed an exponential growth in the number of transistors per IC. With a doubling period of approximately 18 months, this phenomenon, which is called "Moore's Law" holds until today. As products becoming increasingly complex, more products and services emerge. However, product lifecycles decrease rapidly.
- *Cyclic and volatile market behaviour:* Semiconductor companies operate in markets where demand is cyclic. The industry is faced with periods of rapid market growth followed by periods of declining markets. Besides that, as relatively upstream companies in the supply chain, high variability in demand volume needs to be taken into account. Forecasting is very difficult and customers do not always commit to their demand. However, in case of a stock-out there is a great probability that sales will be lost.
- *Asset-intensive production* Capital utilisation is an aspect of great importance in this industry, due to the fact that huge capital investments are required to build new plants. For example, an investment of about EUR 2 billion is required to build a new diffusion plant, or "wafer fab" as they are also called. Therefore, investments in factories are typically related to long-term planning; decisions are taken on a four-year basis.
- *Long manufacturing lead-times:* In the semiconductor industry, the time necessary for production and distribution of semiconductor products is normally between 10 and 15 weeks. This time is much longer than the lead-time customers expect when putting in an order. This forces the industry to strategically manage inventory at various stages in the pipeline.

- *Differentiating customer demands.* Customers have become more and more demanding, as a consequence of increased business globalisation and competition. As products evolve faster and non-traditional competitors enter the market, customer focus becomes a vital driver of loyalty (Tracy & Wiersema 1997). As a result, a "one approach fits all"-policy cannot be used anymore. Products become increasingly customised and a mix of operating models needs to be adopted in order to support the customer's demands. In short, "differentiation" is becoming an industry standard.
- *Fragmentation.* Traditionally, business fulfilment in semiconductor companies is very complex as a result of the large number of products, process steps, and routings through the supply chain. However, complexity is multiplied by customer intimacy and the need for differentiation, global dispersion of production facilities and customers, and outsourcing of production processes. As a result, demanding customers are increasingly faced with increasingly fragmented supply chains. This implies that companies in the semiconductor industry face great challenges in managing their supply chains.

6. Empirical model refinement and partial model estimation

Strictly speaking, "all models are wrong, but some can be useful" (Sterman 2000). All models are imperfect representations of reality, and one can only strive to make them as good an approximation as one possibly can. In system dynamics modelling, this is usually done in a strongly iterative process of, three separate but interlinked activities:

a) Identifying model structure through structured conversations with knowledgeable experts working within the system being modelled, usually through structured workshops and group model-building sessions (Akkermans 1995, Vennix 1996, Akkermans and Vennix 1997).
b) Collecting quantitative data on key parameter settings and time series of performance over time for key model variables;
c) Developing and testing simulation models that represent the structure identified under a) and generate simulated behaviour that can be compared with the historical performance as collected through b).

All this leads to new rounds of a), b) and c), as discrepancies between simulation and historical reality lead to additional data analyses and to additional sessions with real-world system experts. This iterative process is visualised in Figure 6.

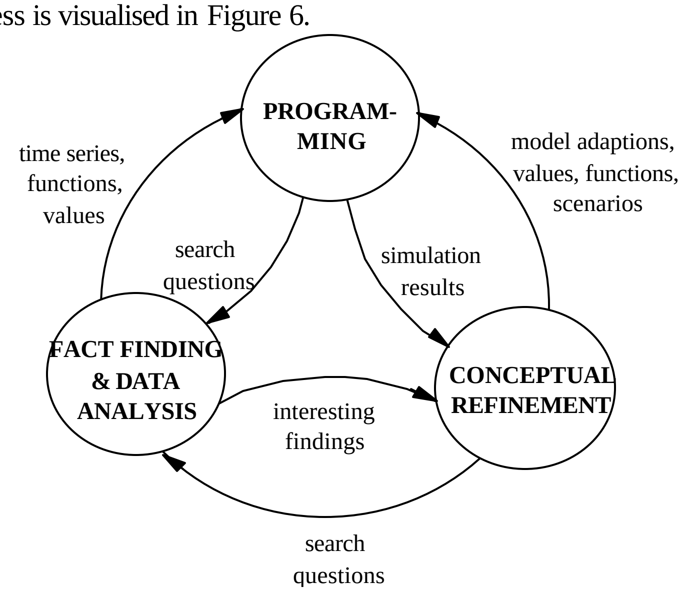


Figure 6: The iterative process of model refinement and validation (from Akkermans 1995)

This is precisely what has been done by the first author, who conducted his Master Thesis research at the central SCM competence centre of this semiconductor company, from where he had frequent contacts with the local business units serving particular market segments (Bezemer 2003).

Most of the key parameter settings for processes, policies and models of human behaviour could be elicited from discussions with representatives from the company. A list of some of the key settings in Appendix 5 and 6. On the basis of these settings, the simulation model as described in Section 4 has been simulated. To calibrate the model further, and also validate if its overall patterns of behaviour fit sufficiently with company data on historical performance, a number of partial model estimation tests have been conducted.

Sales and production output

The overall behaviour of the model is assessed, through visual comparison of the distributions of real world data with simulated date. The assumption made here is that of the simulation model as a black box. Under this assumption, it should hold that when the model is run under the same conditions (exogenous variables) as the real world system, the outputs (endogenous variables) should be broadly similar. In our model, this generates a problem, as almost all variables are endogenous. Similar to Oliva and Sterman (2001), we have chosen to treat customer demand temporarily as exogenous.

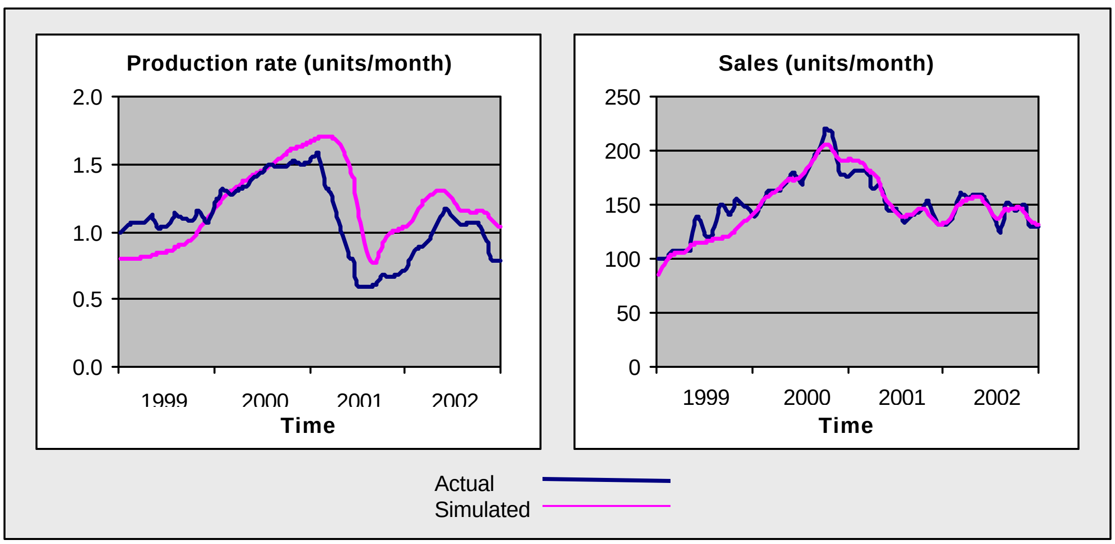


Figure 7: Comparison of historical and simulated data on production and sales

At the case company, time series on supply chain performance from the period of 1999 up until and including 2002 are available. This period reflects the highly cyclic character of the semiconductor industry, since it includes a spectacular upturn and a downturn in the market of over 30% in one year. In order to generate a customer demand pattern over this period, available sales data were translated one month back in time, so as to represent incoming customer orders. Although no hard data are available on this, we know from our interviews that the actually received customer order rate for 1999 and the beginning of 2000 was considerably higher than this translated sales data series suggests. This is because during this period, frequent shortages occurred in the industry (c.f. WSTS 2003). Nevertheless, as can be seen from Figure 7, both simulated sales and production output show a reasonable visual fit with our historical data. The sales data first show a rapidly growing market, which peaks in October 2000. After that, sales decline dramatically.

Supply chain cost: inventory and capacity utilisation
In the long run, the fixed cost of the advanced production facilities is the biggest cost driver in the semiconductor business. As Figure 8 shows, both historical and simulated data on capacity utilisation show that the factories were blowing at full capacity in 1999 and 2000, only to fall dramatically in 2001 and to recover somewhat in 2002 again. As production rates were adjusted downwards later than that the market turned, inventory reached its peak in 2001. Also, as we have seen in Figure 4, higher workloads during this period result in an exponential increase in work in progress, hence, in inventory.

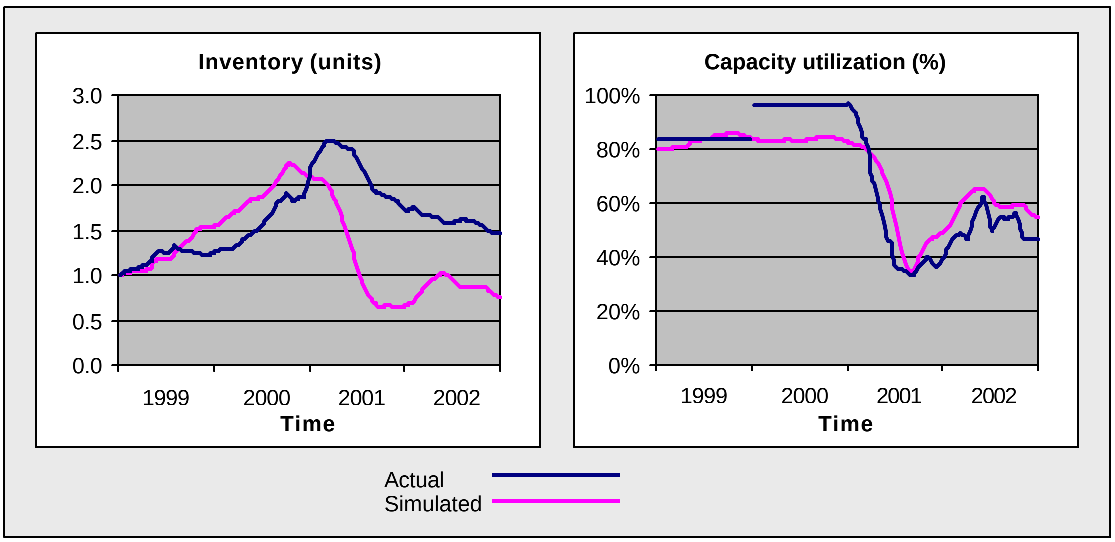


Figure 8: Comparison of historical and simulated data on inventory and capacity utilisation

The fit between simulated and empirical data for capacity utilisation is fair, but the fit for inventory is less clear. For this there may be a number of reasons, of which four key ones are:

- *Value versus* units: The inventory data available is not in units but in value, calculated as units times factory cost price. This cost price is not updated frequently, which creates information distortion. More importantly, when expected sales are high, the fixed cost allocated per product can be low. When expected sales drop, fixed cost allocations will drop. Hence, the strange phenomenon occurs that, in the accounting books, when demand for products goes down, their accounting value goes up.
- *"Factory physics"*: A fundamental relation between WIP, available capacity, and queue-time is used in the model (Hopp, Spearman, 2000). This relation assumes maximum randomness. It seems plausible that, compared to the real world, the model assumes higher levels of WIP (and therefore inventory) are necessary for realising a specific level of utilisation
- *Generic product*: In the simulation model, one generic product is assumed. This makes it possible to "flush" the supply chain empty. In the real world however, a product-mix prevents from doing this. It is likely one has the wrong products on stock.
- *WIP versus final product*: Finally, the historical data add up WIP and final stock into one monetary number. As Figure 9 shows, final product stock rises to its peak later than WIP does. As this final stock also has a higher internal cost price, this effect may play out stronger in value terms.

Most likely, all four of these factors contribute to the mismatch between simulation and reality, but the relative strength at which they do is not well known. What is important to note here though is that, in the real world, it has taken inventory levels at this company almost two year to come back in line again with the sales rate. In our simulation model, this is at least a year, so still quite long compared to a normal stacked lead-time of some 10-14 weeks.

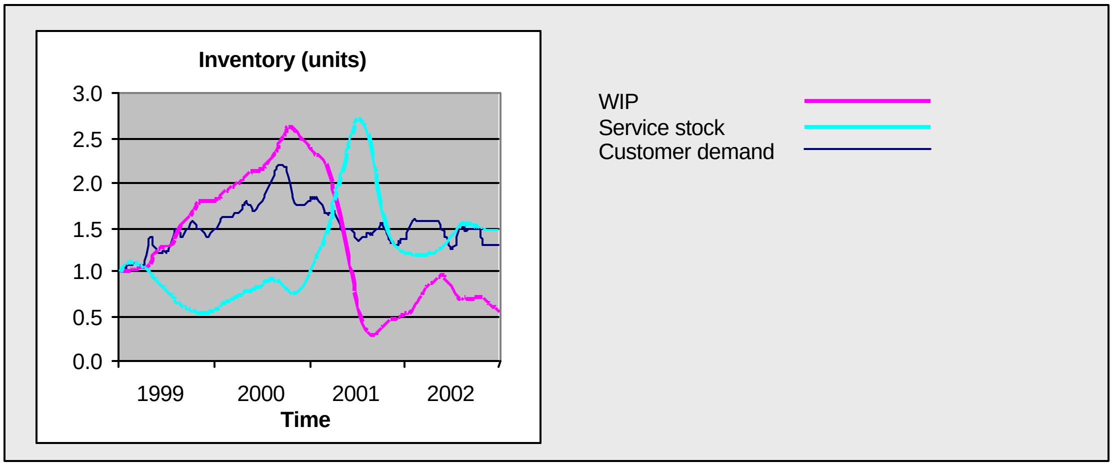


Figure 9: Distribution of WIP and final (service) stock over time

Supply chain flexibility: RLIP

When customer demand is higher than the capacity of the production system can handle, customer demand has to be refused. Obviously, when this happens it suggests inflexibility of the supply chain. At the case company, this was measured as RLIP, or requested line item performance (see Section 4). An RLIP of much more than 80% is always problematic, as this assumes that the company would be able to deliver all products in its portfolio within the target delivery delay of three weeks.

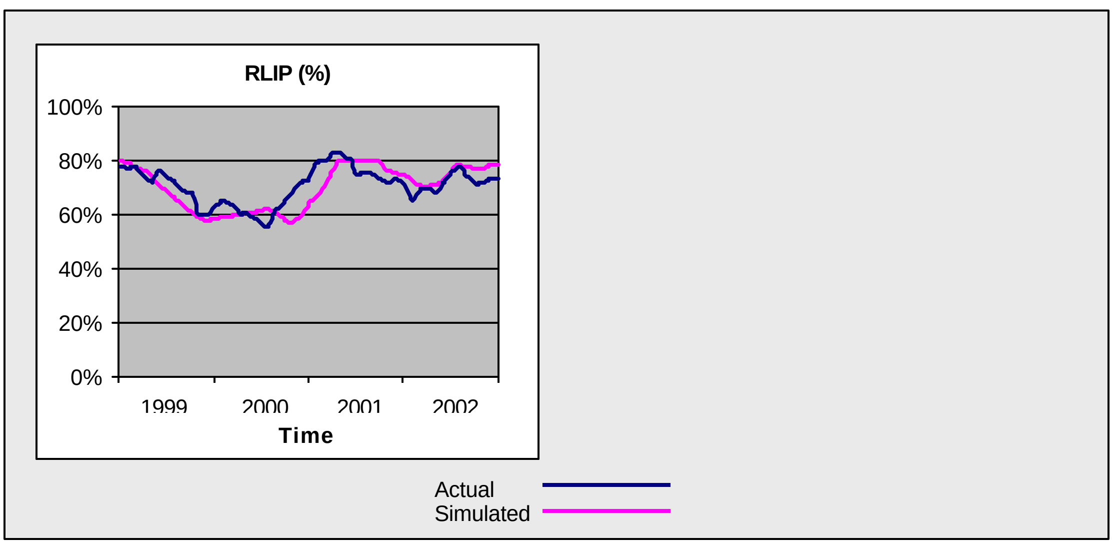


Figure 10: Historical and simulated data on supply chain flexibility in meeting customer demand

As could be expected, during the peak sales period of 2000, RLIP could not be maintained at its target level but dropped considerably. The simulation model replicates this neatly. Interestingly, the historical RLIP also dropped once more early 2002, and again the simulated data follow this trend.

Supply chain delivery quality: CLIP

In theory, CLIP, or confirmed line item performance, could be well at its target level of 95% all the time, even during periods of peak demand. This is because all the company has to do is to deliver the products it knows it has on stock or can assemble shortly to the customer on time. However, as Figure 11 illustrates, this has not been the case. The explanation for this is well-known from the literature on service quality (Oliva and Sterman 2001, Akkermans and Vos 2003) and has to do with the workload that the employees are experiencing: they are well aware that there is a pile of orders waiting to be filled and start making mistakes as a result of this. Figure 11 shows the CLIP as measured at the company versus the inverse of workload as it is calculated in the simulation model. Again, the fit is reasonable, with a slightly less dramatic drop in delivery quality in the model than in reality in 2000, but a swift recovery as market demand reduced sharply towards the beginning of 2001.

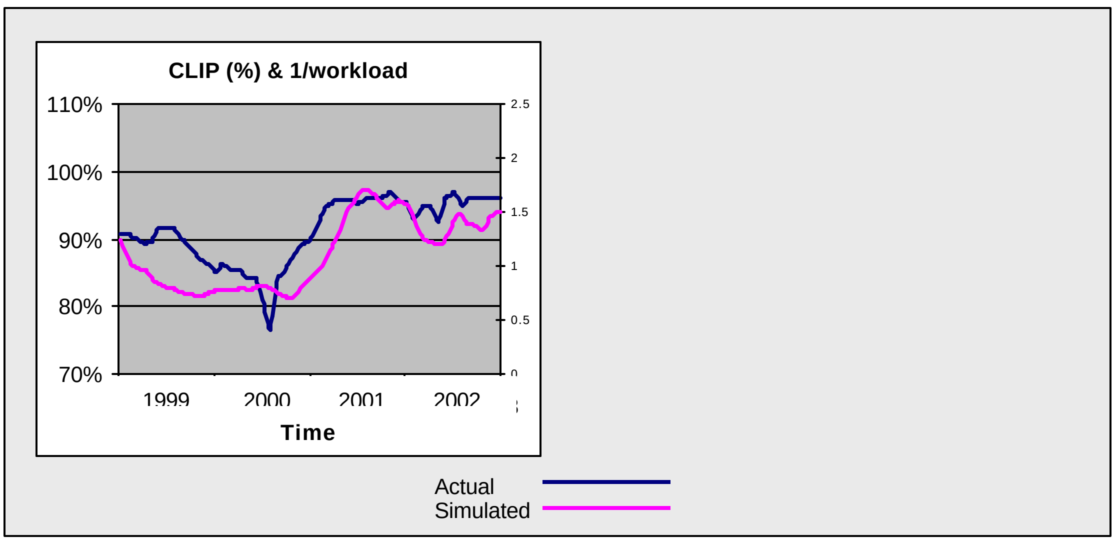


Figure 11: Historical and simulated delivery quality (1/workload)

Supply chain timeliness: cycle times and stacked lead time

Finally, we look at supply chain timeliness. Here we unfortunately only have very limited data on stacked lead-time performance. We know from anecdotal evidence that around the first half of 2001 the stacked lead-time for some key products was about double of what has been measured since the beginning of 2002. This is shown in Figure 12.

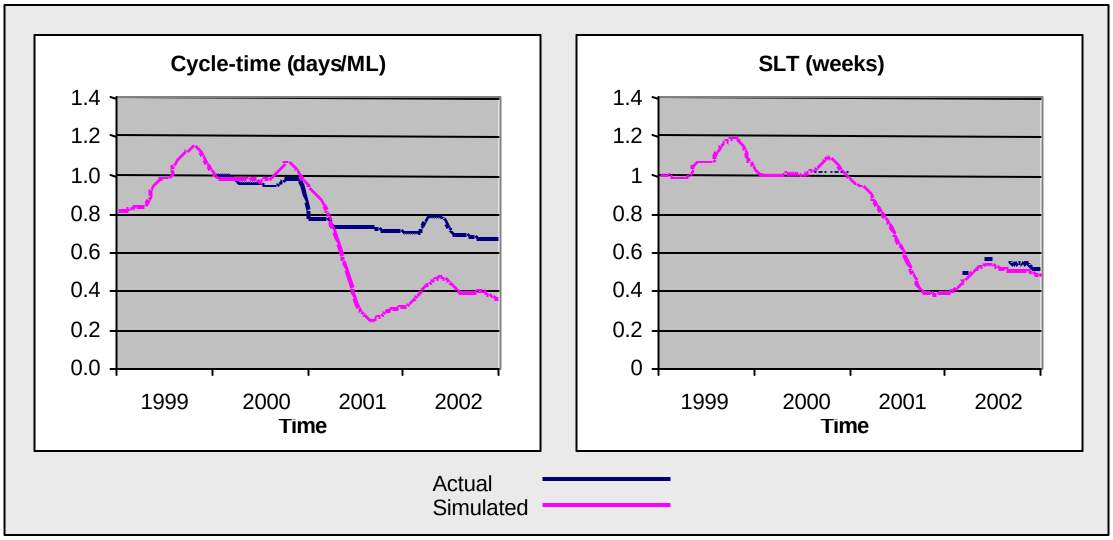


Figure 12: Simulated and historical behaviour of cycle-time and stacked lead-time

More historical data are available on cycle time, but here the issue is that most of what drives cycle time, or "days per mask layer", as the technical term is within the case company, is not related to material flows but to technical progress. Hence, most likely, the relative flat descent of this performance indicator from late 1999 onwards. The sudden drop in the historical data line at the end of 2000 suggests that some workload-related effect has been present, but only at extreme levels, much as with CLIP.

8. Supply chain response delays at different levels

Different delays response levels for different supply chain performance indicators
The topic of this paper is delays in responding to market changes for different supply chain indicators. Based on the behaviour over time charts of Section 7, what can we conclude from this. First of all, in line with our first research question, the following:

Proposition 1*: Regarding delays in responding to market changes for different supply chain performance indicators, the following distinction can be made for different levels of supply chain management:*

- *<u>Operational level</u>: Order acceptance ratio and delivery quality have relatively short response delays (10-20 weeks or 1-2 times the normal stacked lead time).*
- *<u>Tactical level</u>: Inventory levels and stacked lead time have relatively long response delays (1-2 years, or 4-8 times the normal stacked lead time)*
- *<u>Strategic level</u>: Capacity utilisation rate has a very long response delays (2-3 years, or 8-12 times the normal stacked lead time).*

So, we can group supply chain indicators in three levels: those that respond quickly to market changes, those that respond slowly and those that respond very slowly indeed. For instance, capacity utilisation at the case company is, well over two years after the market downturn, still not at its target rate. This is illustrated in Figure 13. This shows how, during the market upturn of 1999-2000, a significant amount of capacity was lined up (simulated data only) to meet this demand growth. As demand dropped in 2001, this capacity did not just disappear overnight. Indeed, only recently has the case company closed some of its most generic and outdated production facilities. This type of delayed response really classifies as , "not with a bang, but with a whimper".

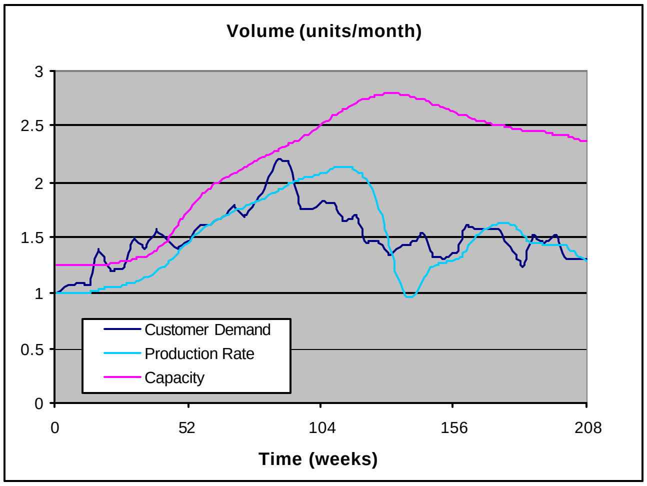


Figure 13: Capacity development and production rates over time

Different drivers for supply chain performance indicators with different delay response levels
But, what is causing these major differences in lengths of delays? Here we have to return to our model structure, as outlined in Section 4. What we find there is that the drivers for these three types of delays are very different, that these drivers themselves have very different response delays and that this explains the differences in response delays for the various performance indicators. Proposition 2 summarises our argument:

Proposition 2*: The fundamental drivers for supply chain behaviour, including the magnitude of the delay in responding to market changes, are, for the different levels of supply chain co-ordination*

- *Operational level (CLIP, RLIP, delivery delay): Order backlog level / Capacity;*
- *Tactical level (Stacked lead-time, stock value): Inventory level / Capacity;*
- *Strategic level (capacity utilisation rate): Market demand level/ Capacity.*

CLIP and RLIP are both driven by some ratio of, on the one hand, the current backlog of orders, and, on the other, the available capacity. As this accumulation of recent demand increases or decreases, so do they follow, almost without delay. Available capacity is also the denominator at the tactical level. Here though the key accumulation is inventory, which is the result of all the production activities initiated in the past periods minus all the sales activity during that same time. As this accumulation rises and falls, so does stacked lead-time. We have seen that the cycle time in the wafer fabs is more or less constant, so the main variable in stacked lead-time is queue time at various stock locations. Finally, at the strategic level there is the capacity utilisation rate. As we have seen, there are delays of several years in bringing new capacity on line and also in dismantling it. So, it is not surprising that the supply chain reacts very slowly indeed to drastic changes in market demand, as it is the ratio of market demand and available capacity that determines capacity utilisation.

Tradeoffs in policies for improving system performance at different SCM levels
So, what can be done to improve performance? Here, no general answers are sufficient since there are fundamental trade-offs to be made. This line of thinking is summarised in Proposition 3:

Proposition 3*: Shortening response delays for different supply chain performance indicators always requires making tradeoffs between performance improvement in one area and deterioration in another, usually at two different levels of supply chain management. The net result on customer satisfaction and future sales, on cost levels and hence on bottom line profitability is therefore unclear.*
The fundamental drivers for supply chain behaviour, including the magnitude of the delay in responding to market changes, are, for the different levels of supply chain co-ordination

- *<u>More (less) restrictive order acceptance</u> leads to lower (higher) backlog and lower (higher) WIP levels and hence to higher (lower) delivery quality and shorter (longer) lead times, but also to lower (higher) demand flexibility.*
- *<u>More (less) restrictive WIP control</u> leads to lower (higher) WIP levels and hence to higher (lower) delivery quality and shorter (longer) lead times, but also to longer (shorter) delivery delays.*
- *<u>More (fewer) buffer stocks</u> lead to shorter (longer) delivery delays, but also to higher (lowever) inventory costs and longer (shorter) stacked lead times.*
- *<u>More (less) aggressive capacity adjustments</u>: lead to higher (lower) supply chain flexibility (RLIP) and lower (higher) WIP levels during market upturns, which leads to higher (lower) delivery quality and shorter (longer) lead times, but also to lower (higher) capacity utilisation levels during market downturns.*

Order acceptance. The low supply chain performance at this company, and within the industry as a whole, during the 1999-2000 period is not just attributable to the unexpected increase in demand. Companies could have said "No" to some of that demand. As they did, their workloads would have remained acceptable, so delivery quality would have remained good. This would have delighted customers and marketeers. Also, as workloads remained under control, WIP levels would stay at modest levels and hence inventory would not have risen so dramatically, as well as stacked lead times. This would have pleased the accounting department. But, there is a trade-off to be made: when customers are told "No, you can't have your product", they are rightfully upset. In our model this tradeoff is not symmetrical: customer dislike it more when they first get their order accepted and later do not get it delivered on time than if their orders are refused straight away.

WIP control. A similar trade-off applies to workload control, so, accepting the orders but not taking more in production that the manufacturing system can handle. Many of the same effects as described with order acceptance would apply: better CLIP, lower stocks and shorter lead-times. But, also, this would lead to dissatisfied customers as their delivery delays would increase as the order backlog, now not immediately channelled through into production, would rise higher and higher. If those orders would still have materialised during the downturn of 2001, when it became clear that much of the offical demand was strongly inflated due to shortage gaming (Lee et al. 1997a, 1997b) one cannot tell.

Buffer stocks. In these days of apparent supply chain anorexia, it is good to mention the blessings of well-placed buffer stocks to dampen demand volatility (c.f. Hoekstra and Romme 1999, Gonçalvez 2002). Buffer stocks can secure short delivery delays even in times of rapid market growth, which pleases customers. Unfortunately though, buffer stocks also cost money, which means a trade-off. More importantly, buffering is only possible for products which are not fully customised, and a significant portion of IC production is precisely that.

Capacity adjustments. With a focus on *customer intimacy* (Treacy and Wiersema 1997), a "capacity cushion" should be created in order to accommodate surges in demand. The line of reasoning here is not just to be ready for the next upturn, but also to win additional demand by pleasing customers with very short lead-times, made possible by planned under-utilisation. On the other hand, if the managerial focus is on *cost control*, capacity should always be trimmed to be in line with demand. Through being conservative with regard to the demand forecast, high utilisation and hence high return on investments can be guaranteed. However, lagging customer demand can lead to erosion of market share. This strategic trade-off can be visualised as shown in Figure 14.

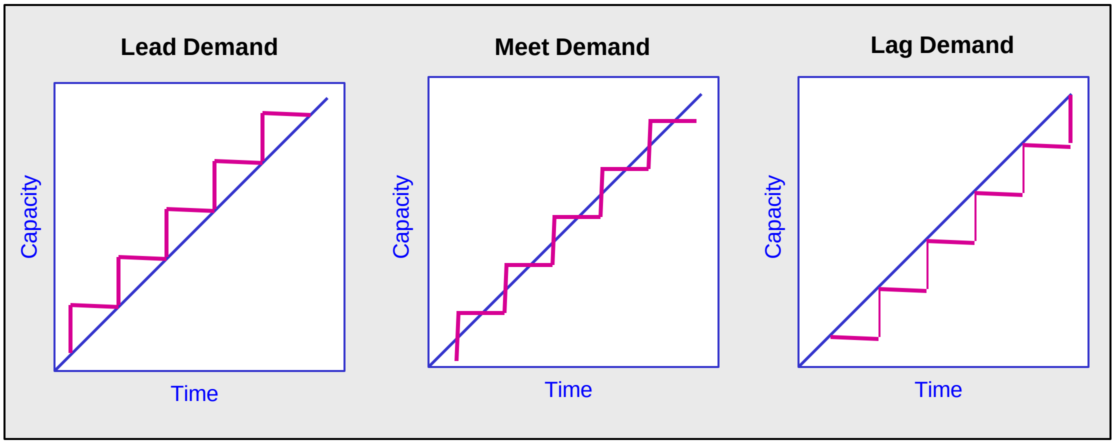


Figure 14: Different strategies for determining capacity adjustment delays

This Figure shows that companies that aggressively pursue increases in market share can follow a *lead* strategy, in which they always have access capacity (the staircases in Figure 14). Or, the can choose to lag market demand, and only have their capacity in line with the market during a downturn.

9. Conclusion

The semiconductor industry is a highly dynamic one, where major surges and subsequent downturns in market demand will remain a fact of life. Semiconductor supply chains must be flexible in dealing with such market volatility. Delays in responding to market changes should be as short as possible. But, such flexibility comes at a price. This paper restates what is commonly known in supply chain management: *there is always a trade-off*. Disappointing some customers to satisfy others better? Investing more in buffer stocks for greater responsiveness but at higher costs? Leading or lagging in adjusting capacity to market demand? How to decide when faced with such multiple, interrelated tradeoffs, is difficult enough for management of semiconductor firms if all the relevant facts and interrelations are known.

This paper has argued that much of the relevant information is not apparent to executive decision-makers in the semiconductor industries. As this is a fast-paced industry, it is often difficult to take a few steps back to see what is actually happening over longer periods of time. This paper has shown that the length of this period can vary considerably. It can be just one or two quarters, in the case of supply chain performance criteria that affect customer satisfaction directly, such as order acceptance or delivery quality. Or this period can be one to two years before inventory levels and stacked lead times recover after a major boom-bust period in the market. It can even be several years, in the case of adjustments of costly production capacity to market fluctuations. Understanding the dynamics of these and others semiconductor supply chain delays is essential if the right trade-offs are to be made. This paper is intended as a contribution to such understanding.

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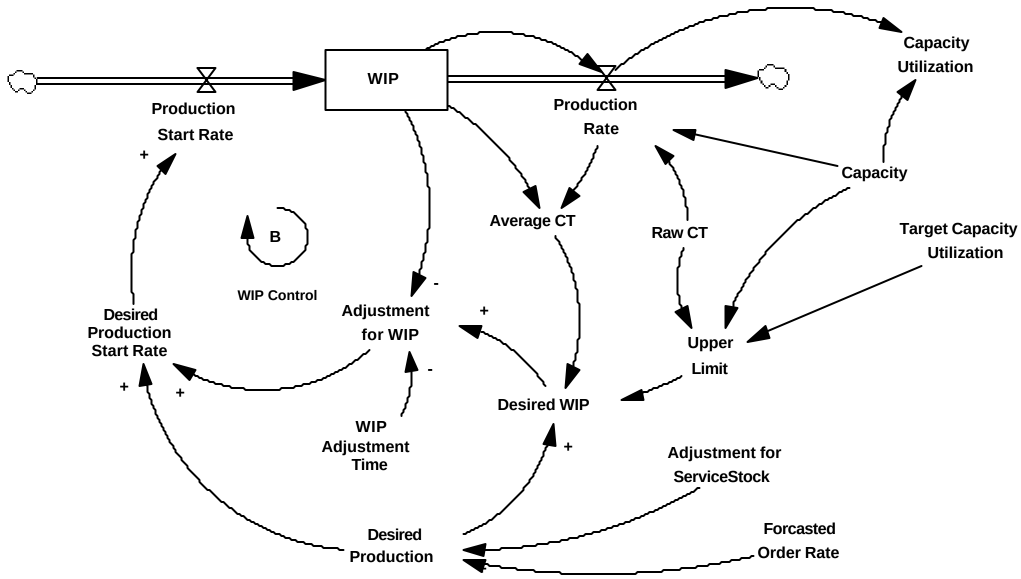
Appendix 1, Structure for production system



Production rate
The formula for calculating the production rate is derived from Hopp & Spearman's (2000) Practical Worst Case. It is determined by the available WIP, the installed capacity and the raw cycle time. The average cycle time and the capacity utilization follow logically the realized production rate.

*Production Rate = (WIP * Capacity) / ((RawCT * Capacity) + WIP)*

AverageCT = WIP / Production Rate

*Capacity Utilization = (Production Rate / Capacity) * 100%*

Production starts
The production start rate is the desired production start rate, constrained to be nonnegative. The desired production start rate is equal to the desired production rate adjusted by the adequacy of the WIP inventory. The desired production rate is the forecasted order rate adjusted to bring the service stock position in line with the target inventory level.

Production Start Rate = MAX (0, Desired Production Start Rate)

Desired Production Start Rate = (Desired Production + Adjustment for WIP)

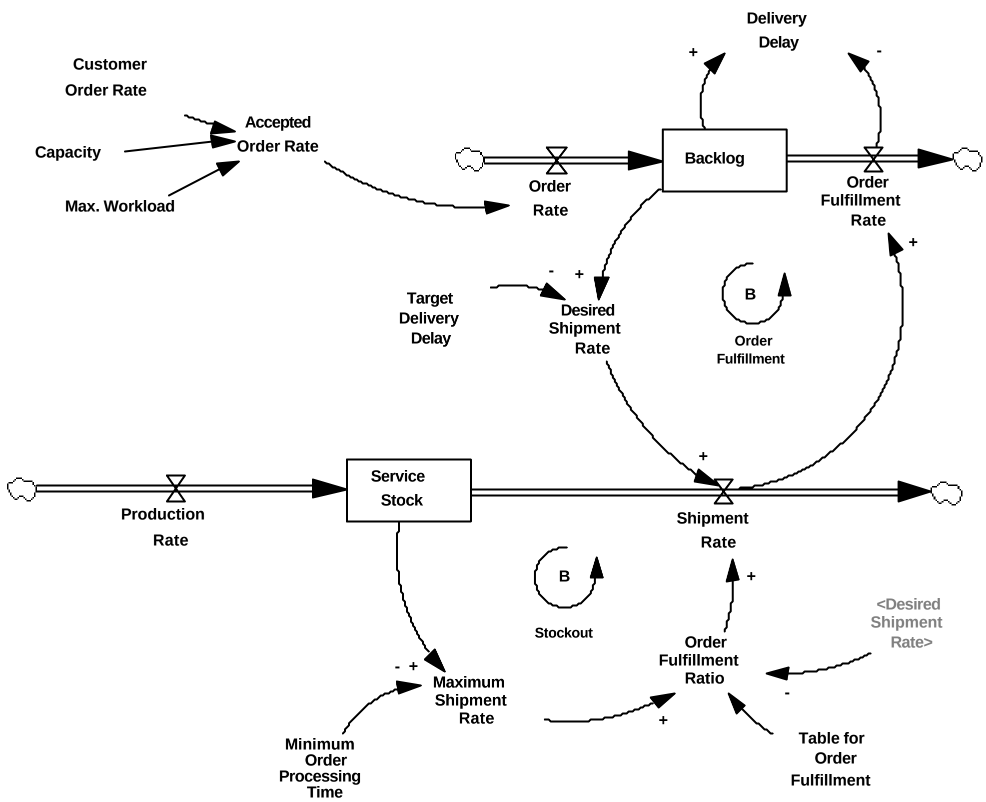
Desired Production = MAX (0, Forecasted Order Rate + Adjustment for Service Stock)

Adjustment for WIP
The desired quantity of WIP is proportional to the average cycle time and the desired production rate. However, in order to prevent the pipeline from overflowing, an upper-limit is set. This limit is determined by the target utilization rate.

*Desired WIP = MIN(AverageCT * Desired Production, UpperLimit)*

*UpperLimit = (Capacity * RawCT * Target UR) / (1 - Target UR)*

Appendix 2, Structure for order fulfilment



<u>Accepted order rate</u>
In order to prevent the system from overflowing, order acceptance is limited to the capacity available for production.

*Accepted Order Rate = MIN(Customer Order Rate, Capacity*Max Workload)*

<u>Shipment rate</u>
The desired shipment rate is determined by the backlog and the target delivery delay. However, endogenous order fulfilment determines the adequacy of the inventory available at the service stock. In addition to that, in order to account for the processes carried out downstream of the die-bank, the maximum rate of shipments the company can achieve is given by their current service stock and the minimum order processing time.

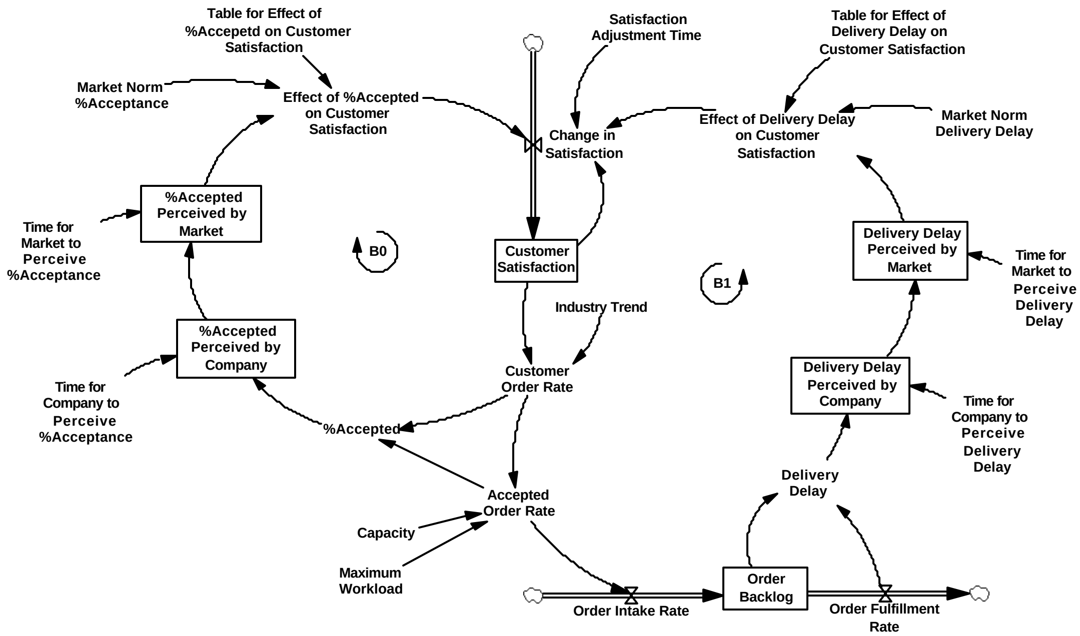
*Shipment Rate = Desired Shipment Rate * Order Fulfilment Ratio*

Desired Shipment Rate = Backlog / Target Delivery Delay

Order Fulfilment Ratio = Table(Maximum Shipment Rate / Desired Shipment Rate)

Maximum Shipment Rate = Service Stock / Minimum Order Processing Time

Appendix 3, Structure for customer demand



<u>Customer order rate</u>

Customer order rate is endogenous. In addition to an exogenous industry trend, which determines the base volume and external variability, customers' satisfaction (CS) with the perceived delivery performance is taken into account. Delivery performance is determined by two feedback loops reflecting product availability (order acceptance and on-time delivery).

*Customer Order Rate = Industry Trend * CS*

*Change in CS = (CS * Effect of %Acceptance *Effect of Delivery Delay) - CS) / CS Adjustment Time*

<u>Effect of %accepted / delivery delay on customer satisfaction</u>

The attractiveness of the firm's products depends on their availability. Long delivery delays (DD) relative to the market norm erodes attractiveness. The delivery delay perceived by the market lags behind the quotes given by the company, which in turn lag the true availability of the product. First-order smoothing is assumed. The same account for the effect of order acceptance on customer satisfaction.

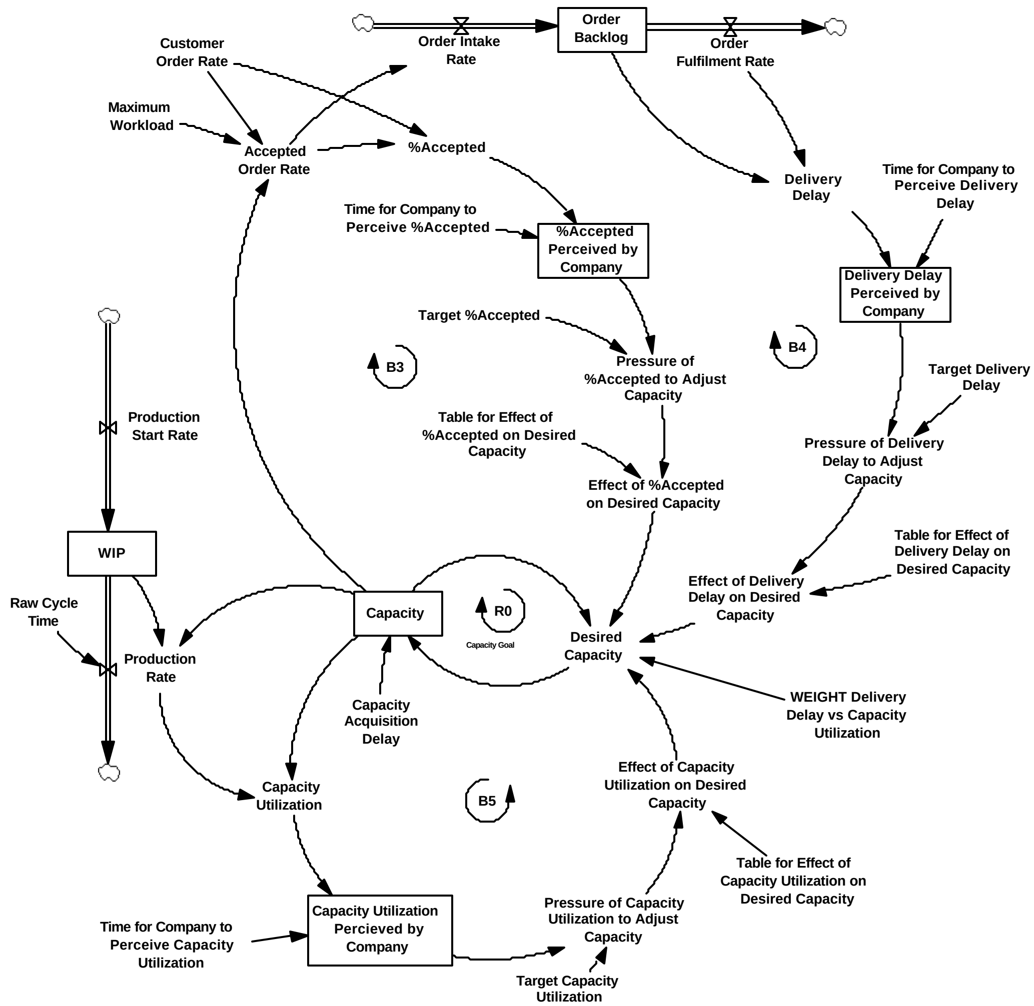
Effect of DD = Table (DD Perceived by Market / Market Norm DD)

DD Perceived by Market = SMOOTH(DD Perceived by Company, Time for Market to Perceive DD)

DD Perceived by Company = SMOOTH(DD, Time for Company to Perceive DD)

DD = Backlog / Shipment Rate

Appendix 4, Structure for capacity management



<u>Capacity</u>

Pressure to adjust capacity arises when the perceived delivery performance (%accepted and on-time delivery) or the perceived capacity utilisation are not in line with the targets set. After a delay, actual capacity will be aligned with desired capacity. The weight determines the relative importance of delivery delay versus capacity utilisation.

Capacity = SMOOTH3I(Desired Capacity, Capacity Acquisition Delay, Initial Capacity)

*Desired Capacity = Capacity*Effect of %Accepted * (Weight * Effect of DD)*
** ((1-Weight) * Effect of Capacity Utilization)*

<u>Effect of %accepted / delivery delay / capacity utilization on desired capacity</u>

For all three feedback-loops, the modelled structure is basically the same as in Appendix 3. First a perception delay is taken into account. After that, a table is used (non-linear function) for calculating the effect on desired capacity.

Effect of DD on Desired Capacity = Table (Pressure of DD to Adjust Capacity)

Pressure of DD to Adjust Capacity = (DD Perceived by Company/Target DD)

Appendix 5, Parameters and values

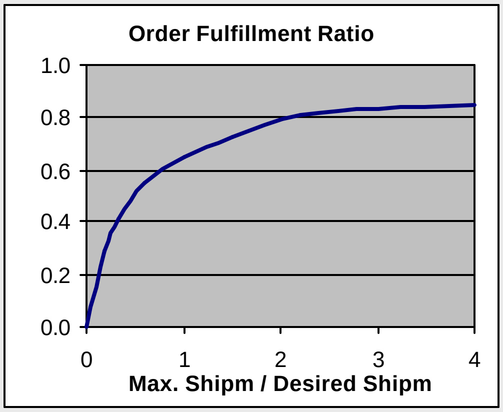
Where possible, "company facts" and "laws" from the literature have been used to determine the values of the model parameters. Typically, process times, company targets and industry standards have been relatively easy to determine. In contrast, the exact details of those parameters reflecting human behaviour have been more difficult to establish. In these cases, the necessary time-series and parameters have been estimated with the help of knowledgeable company representatives.

	Parameter	Value	Source
Facts	Process times - Raw cycle-time (before die-bank) - Minimum order processing time Internal targets - Maximum order acceptance - Target capacity utilization - Target safety stock coverage - Target delivery delay Industry standard - Average delivery delay	 3 weeks 1 week 95% 80% 3 weeks 3 weeks 3 weeks	All these parameters are more or less "facts", which are available in the company. However, often the available level of detail is too high. Information has been aggregated. - Process times are derived from internal measurements. - Internal targets are estimated with the help of the SCM competence centre and business units. - Industry standard is derived from available benchmark information.
↓	Adjustment delays - Forecast - Capacity - WIP - Service-stock Strategy - Strategy chosen (lead = 1, lag = 0)	 26 weeks 26 weeks 20 weeks 8 weeks 0.5	Although these parameters are explicitly used in the simulation model, they have the form of policies in the real world. Therefore they are hard to establish. - Adjustment delays are estimated with the help of business lines and the SCM competence centre. - Company strategy is derived from relevant documents and presentations.
Human behaviour	Company perception delays - Time to perceive customer demand - Time to perceive %orders not accepted - Time to perceive delivery delay - Time to perceive capacity utilization Market perception delays - Time to perceive %orders not accepted - Time to perceive delivery delay Adjustment delays - Customer Satisfaction	 4 weeks 4 weeks 4 weeks 4 weeks 13 weeks 13 weeks 4 weeks	All these parameters refer to human behaviour. Since specific data is unknown, it is most important to use appropriate magnitude. - Company perception delays are assumed to be dependent on monthly internal reporting. - Market perception delays are assumed to be dependent on quarterly reviews.

Appendix 6, Time-series and non-linear functions

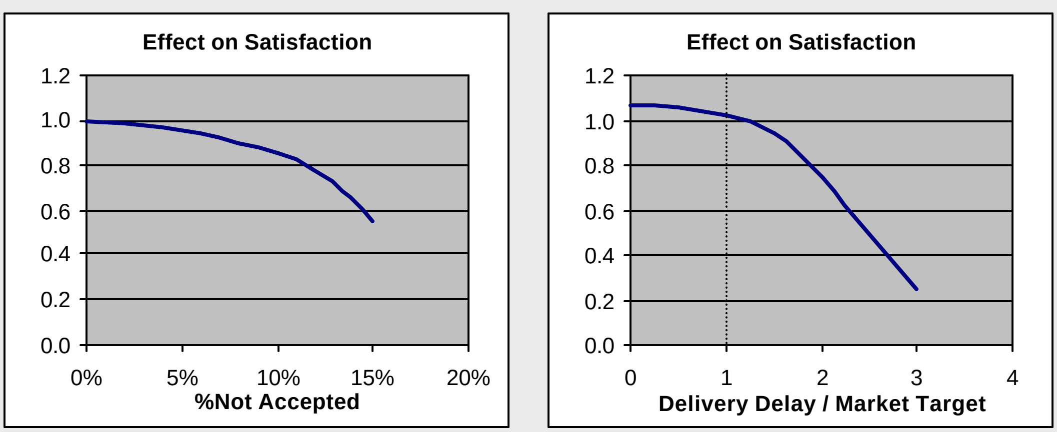
<u>Order Fulfilment</u>
- Table for Order Fulfilment

The non-linear function reflects the following:
- Given the large number of products and frequent changes in the product mix, the company will never be able to have all the right products in its service stock. At best, 85% of the requests can be met instantly.



<u>Customer Demand</u>
- Table for Effect of %Accepted on Customer Satisfaction
- Table for Effect of Delivery Delay on Customer Satisfaction

The non-linear functions reflect the following:
- It is much earlier to lose a customer than to win one. In relation to this, it is modelled that customer satisfaction decreases easier than it increases.
- On-time delivery has a stronger effect on customer satisfaction than order acceptance. This is related the fact that only after order acceptance concrete promises are made. Customers expect the company to fulfil these.



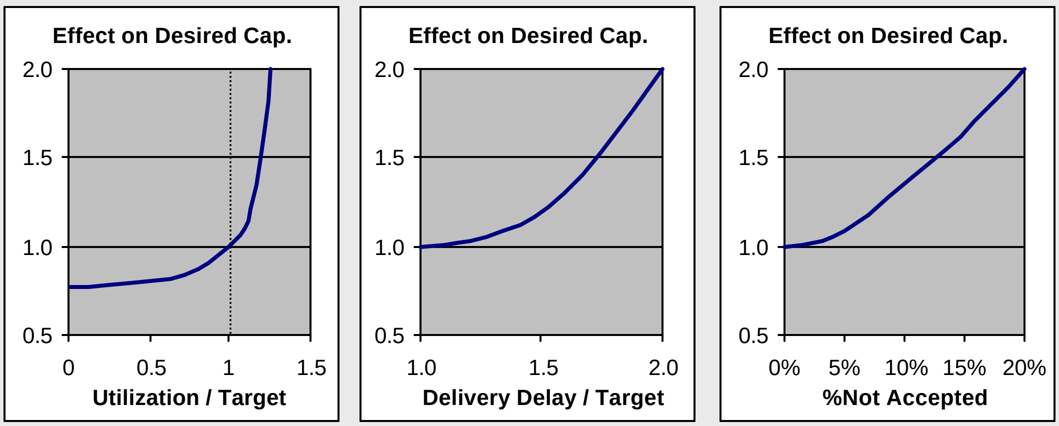
Effect > 1: Customer Satisfaction increases, Effect < 1: Customer Satisfaction decreases

<u>Capacity Management</u>

- Table for Effect of %Accepted on Desired Capacity
- Table for Effect of Delivery Delay on Desired Capacity
- Table for Effect of Capacity Utilization on Desires Capacity

The non-linear functions reflect the following:

- In response to low delivery performance, pressure arises to add capacity.
- In response to over utilization, pressure arises to add capacity.
- In response to under utilization, pressure arises to remove capacity.
- Adding capacity is easier than removing capacity.



Effect > 1: Desired Capacity increases, Effect < 1: Desired Capacity decreases