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Product life cycle-driven supply chain control in semiconductor capital equipment manufacturing

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Manufacturers of capital goods for semiconductor manufacturing, such as lithography equipment, are faced with high market volatility, high annual growth rates and a vicious business cycle. During the product life cycle (PLC) of their products, commercial profiles evolve from high margin / low obsolescence risk to low margin / high obsolescence risk. Many capital goods manufacturers enjoy relatively long product life cycles and therefore can adapt their supply chain control policies to these changing conditions. However, capital goods like lithography machines have high innovation rates and therefore are sold during very short PLCs. For these products, it becomes essential to switch at the right time from a sales department-driven control policy, in the early stages of the PLC, to a stock-driven control of the supply chain in the later stages of the PLC.

This paper presents a theoretical framework for different business drivers and supply chain concepts per PLC stage. Using a system dynamics simulation model this theoretical framework is tested on an real-world example of a manufacturer of lithography equipment. Effects are shown on total profitability over the PLC for different switching points from sales department-driven supply chain control to stock-driven supply chain control.

1. Introduction

All capital equipment manufacturing industries are characterized by high demand volatility and upstream demand amplification. For the U.S. machine tool industry, for instance, year-to-year change in volume of orders placed has been estimated at 37% [1]. This makes effective supply chain management (SCM) very difficult. In the good years, all customers want everything at the same time, rendering the problem of obtaining sufficient amounts of components and subassemblies in a timely manner a major challenge. During a downturn, orders to suppliers have to be cancelled as a result of worsening sales forecasts and order portfolios. Inventory levels increase and production lines are standing idle while debt accumulates. Not surprisingly, many manufacturers of capital equipment do not survive these wild fluctuations. In the U.S. machine tool industry, some 40% of the firms that existed in the mid-1970s have since disappeared through acquisition or dissolution [1].

Fortunately, most capital equipment manufacturing firms are enjoying long product life cycles (PLCs). One recent study found that for industrial controls the average time interval between major product redesigns was over five years [2]. This is fortunate because short product life cycles of one to two years, as are common in high-clockspeed [3] industries such as PC or TV manufacturing [2], create significant supply chain management challenges. SCM requirements are different in each stage of the lifecycle [4]. In the early stages, being there first is essential and price is relatively unimportant. In the maturity stage, reaching high volumes of output is most important. In the decline stage, the risk of obsolete stocks is highest.

Conveniently for supply chain managers in the capital equipment industry, their relatively long PLCs make it possible to gradually adapt to these different requirements for different PLC stages. Moreover, since with long PLCs the growth and maturity stages last far longer than development and decline, the SCM focus can be on the requirements of the former.

There is, however, at least one capital goods industry segment that is faced with both very high demand volatility *and* very short product life cycles at the same time. This segment consists of firms that produce state-of-the-art manufacturing equipment for the semiconductor industry such as wafer steppers and other lithographic equipment. For these firms, the business cycle is as vicious as it gets but, in addition, its product life cycles are as short as those of their customers, the IC manufacturers, i.e. no more than one to two years. Interestingly though, here too SCM policies have tended to be focused on dealing with the vicissitudes of the business cycle and not on the changing demands of the different PLC stages.

This article argues that manufacturers of lithographic production equipment might benefit from a better understanding of the different supply chain control (SCC) requirements in the different phases of the product life cycle. It claims that having different SCC policies for the development, growth, maturity and decline stage yields superior business results to having the same policy for the entire product life cycle. Lead times can be shorter due to aggressive buildup of work in progress (WIP) in the development and growth stage; obsolete stocks can be reduced at the end of the PLC due to lower WIP and lower target service levels in the decline phase.

The rest of this article is structured as follows. In Section 2 we examine the supply chain dynamics of the market for lithographic equipment more in detail. In Section 3 we discuss PLC-driven supply chain control policies in general. Next in Section 4 we introduce a system dynamics (SD) simulation model of a part of the supply chain for a capital equipment manufacturer faced with short PLCs as well as long lead times in its supplier network. In doing so, we will limit our analysis to a single product type over its product life cycle.

In Section 5 we apply the general supply chain model to a real-life case of a lithography equipment manufacturer. We present a calibrated and validated model of the manufacturer's supply chain, based upon a combination of historical company data and input from group model-building workshops with company representatives. In Section 6 we present a quantitative comparison between the result obtained with the historical – PLC stage indifferent – way of working and the results obtained with the PLC-driven supply chain control policy. We show that both a purely sales-driven SCC policy and a purely stock-driven SCC policy are outperformed by a PLC-driven SCC policy. The results also suggest that the switching point from sales-driven control to stock-driven control can best be chosen immediately at the end of the growth phase.

Finally, Section 7 presents the conclusions, including promising research opportunities for expanding the concept of PLC-driven supply chain control into other areas.

2. Business dynamics in semiconductor capital goods manufacturing

The electronics industry recently surpassed the automotive industry to become the largest basic industry in the world after agriculture. At the heart of this industry lies the manufacturing of semiconductor devices. The semiconductor market is expected to be greater than $250 billion in the year 2000 and has maintained an average annual growth rate of 15% over the last 15 years. This market is a highly competitive one, driven by global technological innovation, a crucial role in which is played by lithographic equipment that enables firms to produce the most advanced, and hence most profitable, integrated circuits (ICs).

The market for lithographic equipment is a highly complex one from a supply chain control perspective, for at least three reasons. Firstly, it continues to experience high growth rates of 15-18%, generating constant growth pains for firms operating in this market. Secondly, it is faced with the same steep business cycle as most capital equipment firms, which is caused by upstream demand amplification [1,5,6]. Figure 1 shows how demand amplification works out in the semiconductor industry. It contains de-trended normalized industry sales for the past two decades for semiconductor manufacturers and the providers of their production capacity, the semiconductor equipment manufacturers. Year-to-year change of these sales is 16% for semiconductors, but 25% for semiconductor equipment. If we then look at the lithography subset of semiconductor equipment manufacturers, we see an even stronger amplification: 48% year-to-year change. Please recall that this is considerably higher than the demand amplification experienced by the US machine tool industry, 37% year-to-year change [1].

Semiconductor Equipment Sales (Normalized De-trended)

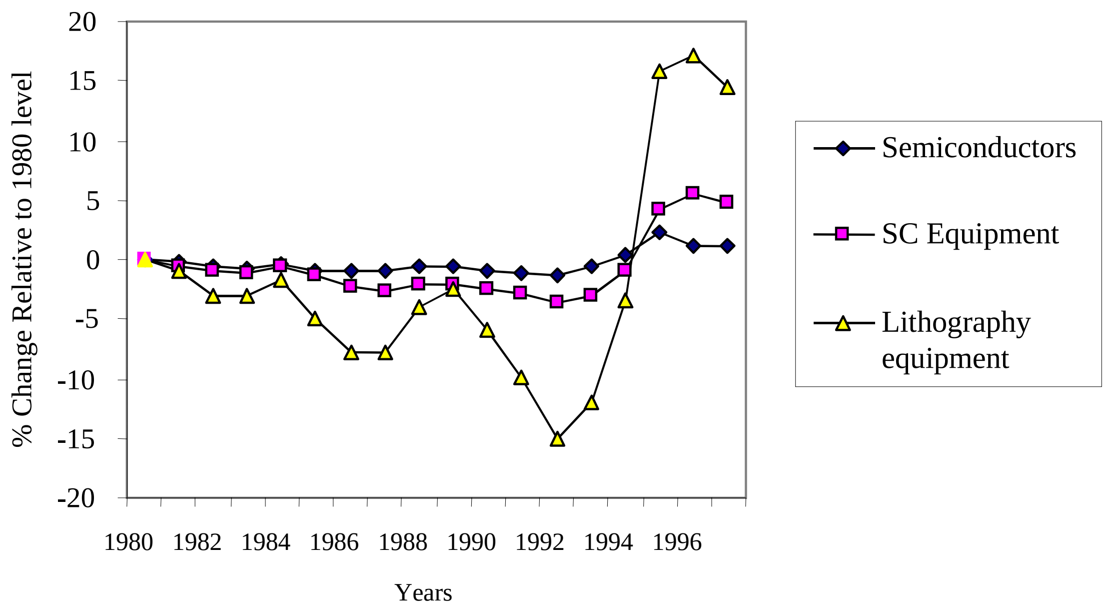

Fig. 1: Demand amplification in the semiconductor equipment industry (Source: Dataquest)

A third reason why supply chain management is so difficult for lithography equipment manufacturers is the short product life cycles they are facing. The highest profit margins for the integrated circuit (IC) producers can be made with the technologically most advanced IC-designs. These however, can only be produced with the technologically most advanced equipment. The increase in demand for these most advanced ICs has therefore created a demand for the latest technology in manufacturing equipment. In the last decade, this has led to a strong increase in the frequency of introduction of new equipment types. Between 1981 and 1996, 5 DRAM generations have been developed, resulting in a three year product life cycle, which is easily half the normal PLC duration for capital goods.

The strong demand for the latest technology has two supply chain control consequences. Firstly, state-of-the-art equipment has to be replaced faster by newer types, which shortens the product life cycle, steepens production ramp-up and accelerates ramp-down. But secondly, because the newer types tend to have higher throughput capacities than older ones, demand per type does not grow as rapidly as the demand for high end ICs does. Hence, the average production number per type tends to be stable or even drop. So increasingly, fewer but more complex machines are developed, produced and sold in ever-shorter time frames.

3. Supply chain control for capital goods with short life cycles

3.1. *Business opportunities and risks over the product life cycle*

The basic characteristics of the different stages of the product life cycle are textbook knowledge. The first few rows of Table 1 are based upon an exhibit from one such textbook [4]. It shows how market growth and degree of technological change will evolve over time from very great to nil. Equally well known are the different management priorities over the PLC. In the development stage, capturing market share is all-important and hence time-to-market is crucial, whereas in the maturity stage volume becomes more important than timeliness. Price erosion is a serious risk here, whereas price is usually not an issue very early in the PLC. In the decline phase, volume means no longer opportunity but risk, i.e. risk of obsolete stocks.

Table 1. Different business and supply chain control characteristics over the PLC

Stage	*Development*	*Growth*	*Maturity*	*Decline*
Market growth rate	Slight	Very large	Moderate to nil	Negative
Technological change in product design	Very great	Great	Moderate to slight	Slight
Key business opportunity	Capturing market leadership	Capturing market share	Capturing market volume	Capturing market legacy demand
Key business risk	Investing in wrong technology / product	Failing to manage ramp-up	Getting caught in price war / price erosion	Obsolete stocks
Key SCC priority	Minimize time to market	Minimize lead times	Maximize production volume and minimize costs	Minimize obsolete stocks

Adapted from: [4].

3.2. *Supply chain control policies over the product life cycle*

A generally accepted control concept for assembly products with dynamic demand is Material Requirements Planning (MRP) [7]. With MRP, the supply chain is controlled by releasing production orders for components, subassemblies and final product to realize the Master Production Schedule (MPS), taking into account batch sizes and manufacturing lead times. In this control concept, the Master Production Schedule plays a critical role. The MPS is a statement of future output over a horizon that covers the stacked lead-time of the manufacturing supply chain. This output statement is not equal tot the demand forecast, nor is it equal to the optimal manufacturing level. According to the MRP-II philosophy, the MPS balances the need for market responsiveness, as expressed by the Marketing and Sales function, with the need for stable and predictable production levels, as pressed for by Manufacturing [8]. This balancing act is accomplished in a negotiation process between Sales and Manufacturing, in which also Finance may be involved.

A two-stage PLC-driven supply chain control concept. Now, let us consider a product type with a short product life cycle and let us define ''short'' as the situation where the anticipated time span of the maturity phase is about the same as the stacked lead-time of the supply chain, the stacked lead-time being the sum of the separate manufacturing lead times in the total supply chain. This means that, at the start of the maturity phase, the components that are produced upstream will be part of the end products sold at the start of the decline phase. For products with such a PLC profile, the whole life cycle can be split into two distinct control phases. The first control phase comprises of the development and growth phase; the second comprises of the maturity and decline phase.

Control concept during the development and growth phases. During the development and growth phase, there is a low probability of product obsolescence but high uncertainty about potential demand. Most importantly, there is a high premium on short time to market and early product availability in the market. Therefore, during this phase the marketing and sales function should be leading in the setting of the MPS, even if it is overly optimistic regarding potential sales. Since in this phase, the costs of missed sales are high and the cost of inventory are low, the sales department should have the lead in the formulation of the MPS during the development and growth phases. In fact, it would not be harmful during these phases if the MPS were simply dictated by the sales department. This is what we call the sales department-driven SCC policy.

Control the maturity and decline phases. This picture totally changes when the maturity phase is entered. A signal for this could be that the number of products sold remains stable during a number of months. Now that we have entered the maturity phase, we have to prepare for the decline phase, given the stacked lead-time of the supply chain. Therefore, the emphasis in controlling the supply chain should now shift from creating availability in the market place to avoiding obsolete components, subassemblies and final products still in the supply chain at the end of the PLC. Control of the supply chain will be based on an estimate of the total demand over the remainder of the PLC, with the explicit aim of avoiding obsolete echelon stock at the end of the life cycle. This is what we call the stock-driven SCC policy.

4. A generic system dynamics model of a capital goods manufacturing supply chain

In this section we present the essential characteristics of a generic model of a capital goods manufacturer and its suppliers that can be used to evaluate supply chain control scenarios under conditions as are experienced in the lithography industry, i.e. steep business cycles, short product life cycles and long supply lead times. The description of the complete system dynamics model would take much space without adding substantially to an understanding of the essentials of the behavior of the system. A complete listing of the SD model is given in a separate working document and available upon request.

4.1. *Model structure*

Our model represents four actors in an interorganizational supply chain: the equipment manufacturer, one of its key suppliers of subassemblies and two second-level suppliers of components to that supplier. Each of these actors has a separate representation of its:

1. Production system;
2. Production capacities;
3. Production control modules.
4. Production output.

1. *Production system*. This means the steps required in manufacturing the product. For the equipment manufacturer and for its main supplier, this is an assembly line of modules. The assembly line of the supplier is fed by output from the two second-level suppliers, where the basic components for the modules are manufactured in a job shop production structure.
2. *Production Capacities*. Available capacity for all four actors consists of both people and machines, although these two production factors need not be bottlenecks in every instance. Available capacity is increased by ordering additional capacity when schedule pressure reaches a threshold value. In the meantime, overtime is used to compensate for capacity shortages. The required capacity per unit of product decreases over the product life cycle due to learning curve effects, which are discussed further down. Interaction with other products produced is modeled in each stage as a maximum on the fraction of capacity spent on this product type.
3. *Production control*. The supply chain is driven by the master production schedule (MPS) plans of the equipment manufacturer, which in the model are externally defined. In our default model, these MPS-data are input for an MRP-algorithm generating production orders and purchasing orders. The purchasing orders are passed to the planning level of the main supplier with an information delay. At this level, the purchasing order is again processed with an MRP-algorithm, generating production orders and purchasing orders. The former is input for the physical process level, the latter are — after again an information delay — input for second level suppliers. These use this information for their own production control and procurement/purchasing. In the model, they are always able to secure sufficient materials for production.
4. *Production output*. The production output of the assembly stages is modeled as a pure time delay of the production orders, with the time delay depending on the capacity allocated to the production order. Production orders are equal to

requirements from the MPS system with a possible delay if modules of the supplier, or components from the component manufacturers are not sufficiently available. The production output of the component manufacturing stages is modeled as a fraction of the work in progress, where the fraction depends on the amount of capacity allocated to the component orders for this product.

4.2. *Product life cycle representation*

Over its lifecycle, this system is subject to a number of strong non-linear effects, generated by the interplay of multiple feedback loops. Therefore, developing a system dynamics model to capture adequately these effects and interdependent feedback loops appears a logical choice, since system dynamics is intended specifically for such types of situations [9,10]. One such cause of nonlinear dynamic effects is the product life cycle. In our generic model, two product life cycle effects are represented.

Firstly, as the product matures, so will its design, reducing the number of engineering changes to be absorbed by the supply chain [11,12]. Engineering changes require additional capacity in the manufacturing system and can lead to additional delays in output. Figure 2 provides the main causal relationships as described in this section incorporated in the generic system dynamics model of the four stage capital goods supply chain.

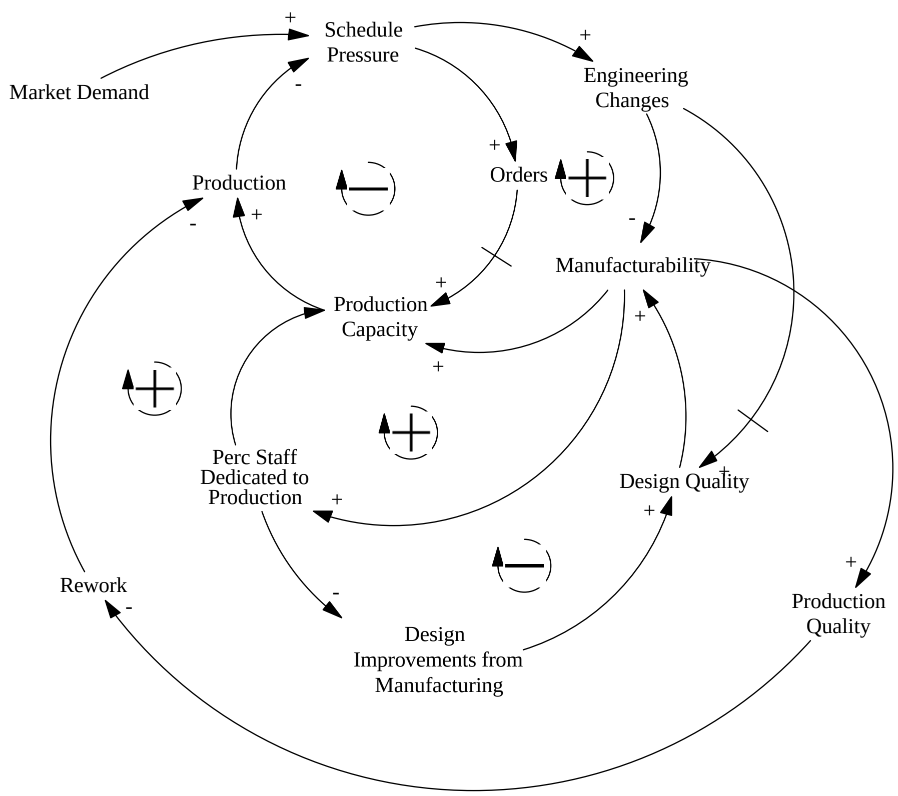

Figure 2: Main product life cycle-related causal relationships in the generic SD model

5. A real-world example of PLC-driven supply chain control

We have used the generic SD model to represent and analyze a part of the supply chain of a lithography equipment manufacturer. This specific model we use to investigate its supply chain control performance over the PLC of a particular product and to compare this performance with the performance that can be obtained with a PLC-driven supply chain control.

5.1 *A typical lithography company: Lithography Co.*

The company studied here, which we will label Lithography Co., has been successful since its inception in the mid-1980s, but not without serious ups and downs, which even the logarithmic scale in Figure 3 cannot hide. In general, one can say that this company is driven by its very aggressive and optimistic marketing function, which stretches company resources time and time again but has led the way to consistent increases in market share for the last two decades. However, in its downturns this company has also repeatedly been on the brink of insolvency because of its high obsolete stock levels.

As Figure 3 illustrates, this company can be seen as typical for the lithography industry as a whole because it too has experienced high annual growth rates (per annum on average), steep business cycles (an average year-to-year change of no less than 70%) and very short product life cycles. In fact, its PLCs are even considerably shorter than the industry average, with ten new product platforms being introduced in the last eight years. In effect, it has implemented a ‘’platform’’ product development strategy [13], where different product types form the base of a product family that can be leveraged over several years.

Annual Sales Lithography Co. (Normalized on Logarithmic Scale)

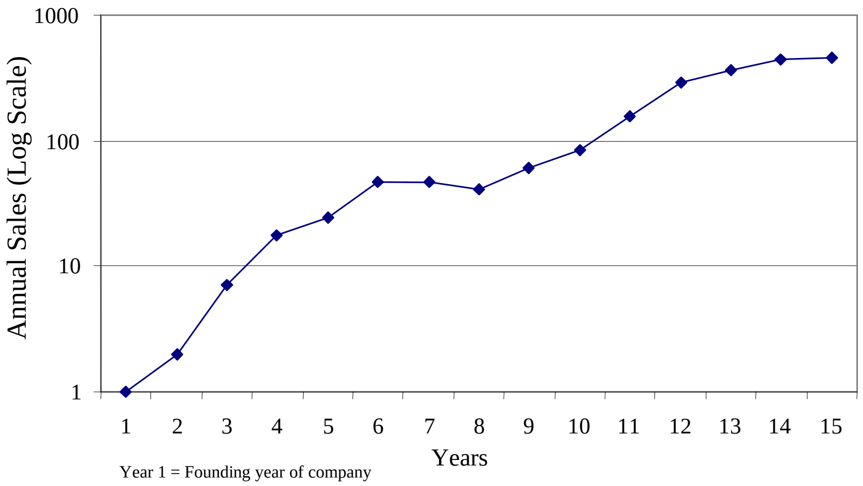

Fig. 3: Annual sales growth at Lithography Co. (Source: company data)

5.2. *Modeling approach*

The generic model described in the previous section was detailed, calibrated and validated for this company's main current product line. A crucial role in this process was played by so-called group model-building workshops [14,15]. In these workshops, which were facilitated by the authors, representatives participated from the different companies involved. As in our generic model, these were the equipment manufacturer, one of its main suppliers and two of its second-level suppliers.

The group-model building workshops came in three different varieties. Firstly, workshops were conducted on a firm-by-firm basis. Purpose of these was to detail out the overall model structure as described in Section 4. Next, group model-building workshops followed that involved all the participating companies. Here the results from the firm-specific workshops were presented to each other, discussed and refined. This resulted in the clarification of numerous operational misunderstandings, but in terms of the overall model structure only minor changes had to be made. Also, key quantitative data for were collected. On the basis of these inputs, the authors could calibrate and validate a quantified system dynamics model of this extended supply chain and run simulation experiments on it, i.e. develop a number of scenarios.

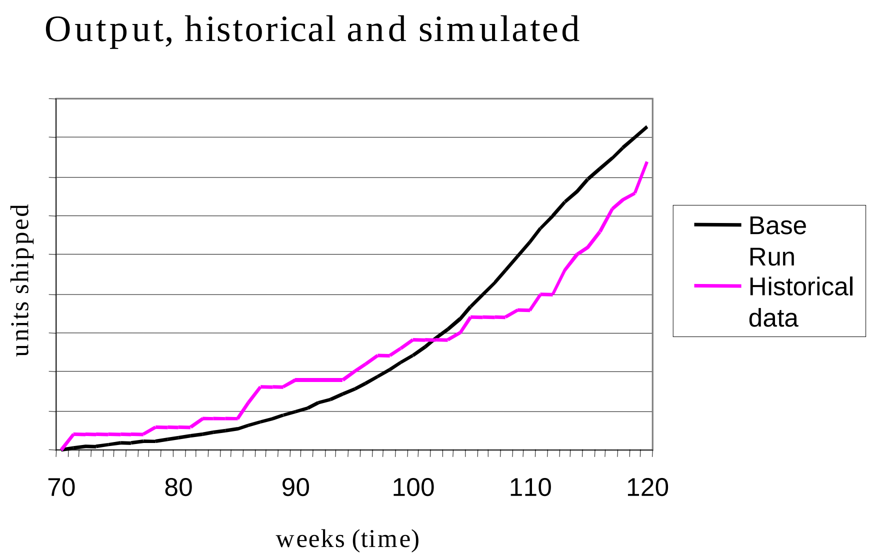

Fig. 4: Validation of simulation model by way of historical time series comparison

5.3 Model validation

In the third type of group model building workshop the resulting simulation model was validated in two ways [16]. Firstly, in terms of its structure (Did it represent the business processes involved adequately?) and secondly, in terms of its behavior (Did the simulated base case follow the same pattern of behavior as the historical data indicated?). Figure 4 shows one example of the latter form of validation. It depicts units shipped according to the base run of our calibrated simulation versus the available historical data on shipment schedules.

All data concern the production of a significant type of new equipment, and are not influenced by demand for older types or service parts. The graph represents the period between the beginning of the growth phase and midway the maturity phase when historical data was no longer available. As can be seen from Figure 4, the model and history display similar behavior. Admittedly, the cumulative actual output grows less smoothly than the model output. This is so because, in reality, between weeks 90 and 110 a number of interrelated design problems were revealed which had to be solved concurrently. As a result, output during this period slowed down.

6. Policy analysis

In this section we compare the supply chain performance obtained with the current control policy with performance under a PLC-driven policy. The policies are applied to the calibrated systems dynamics model of the lithography equipment supply chain as described in the previous section.

6.1. Policy modeling

We have analyzed the MPS numbers that have been used by the equipment manufacturer over the PLC of this particular product. The MPS consists of the required monthly output of a horizon of 16 months, and is updated each month. The numbers in the monthly MPS's can be fairly well modeled as a linear function:

$$M(t,\tau) = a_t + b_t \cdot \tau \qquad (1)$$

where:
$M(t,\tau)$ is the required output in period $t+\tau$, according to the MPS at period t
a_t, b_t parameter values that can change each period that the MPS is updated.

The real numbers in the successive MPS's have been used to estimate the (a_t, b_t) values in the above model. Since the numbers in the real MPS are mainly determined by the sales department, we call (1) the sales department-driven MPS. The continuing optimism of the sales department regarding future sales is reflected in b_t-values that are consistently larger than zero.

The performance obtained in the systems dynamics model with the sales driven MPS is the benchmark for evaluating the performance obtained with an alternative MPS where at some point in the product life cycle, the MPS no longer emphasizes maximizing sales, but emphasizes avoiding obsolete stocks at the end of the PLC. In our research this has been modeled as follows. At the start of the PLC, the sales department driven MPS is used, up to some switching period t_s. For all $t \geq t_s$ the impact of the sales department on the MPS is eliminated. Instead in the MPS it is assumed that demand will continue at the present level. In formula:

$$M(t,\tau) = a_t \qquad (2)$$

Note that this MPS policy not only negates after t_s the requirements of the sales department regarding future output, as represented by the factor $b_t \cdot \tau$, but also neglects all possible information about future demand that might result from knowledge of the position of the product in its life cycle. If it would be possible to determine with sufficient accuracy the position of the product in its PLC, an MPS reflecting this knowledge could be used, which might considerably improve the supply chain control performance. In this research we investigate a simple variant of such a PLC-knowledge driven MPS, which only makes use of either the output requirements given by sales, or the actual sales. We call this the PLC-driven supply chain control policy.

6.2. Policy simulation

The sales department-driven supply chain control policy and the PLC-driven supply chain control policy have been applied to the system dynamics model of the supply chain in a simulation over 200 weeks. For our model analysis, exogenous demand has been a key input for the model. This is one entire PLC of 200 weeks. The pattern is constructed from historical data going until week 200. The demand data from week 70 to 90 show a steep climb, and can be regarded as depicting the growth phase. The maturity phase with its consistently high levels of demand continues until week 130. In the decline phase, the drop in demand is sudden and severe: about 75% between week 130 and week 145. The simulation ends in week 200.

As performance measures we have used: total sales as a function of time, total supply chain stock at the end of the simulation period, and total gross profits at the end of the simulation period. Total gross profits are determined by subtracting manufacturing costs for machines sold and stock obsolescence costs from sales revenues for machines sold over the life cycle. Costs of manufacturing include the effects of redesign and learning on production efficiency; costs of obsolescence stocks include the effects of reworking obsolete stocks for service in new products. The numbers shown in the diagram in this paper have been rescaled for reasons of confidentiality.

First a simulation has been performed with the sales department-driven SSC policy. Figure 5 shows the resulting cumulative sales as a function of time, where the 200 weeks are split up in the development phase, the growth phase, the maturity phase and the decline phase. Cumulative sales and stocks have been normalized as a percentage of historical sales. Cumulative gross profit has been normalized at our estimation of historical cumulative profit. This simulation run has been used as a reference for the simulations with the PLC-driven SSC policy.

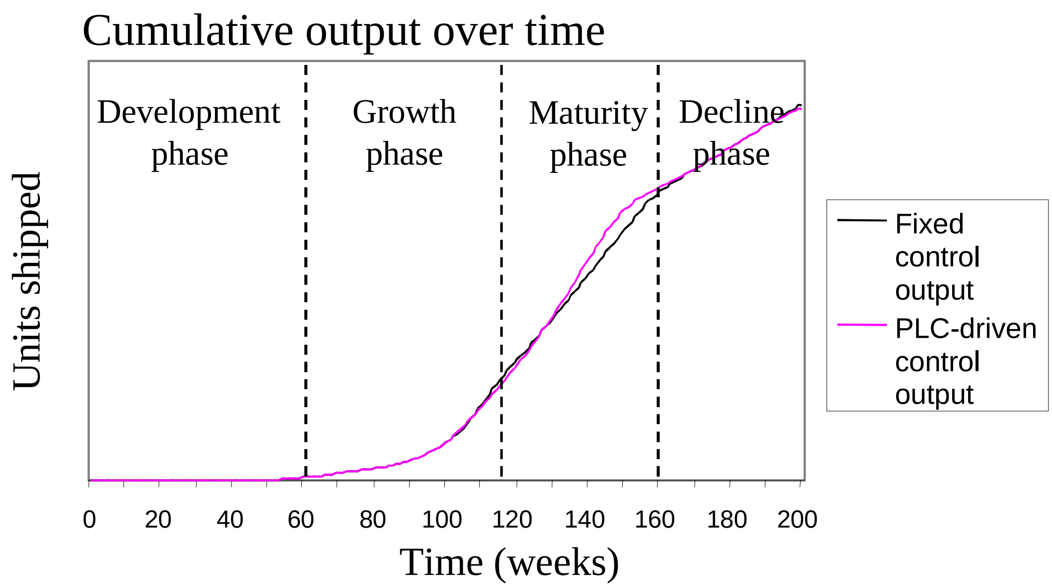

Figure 5: Model simulation with a fully sales department-driven SCC policy

Next, we have performed 50 simulations to investigate the performance of the PLC-driven SCC policy. The results from this analysis are shown in Figure 6. Each simulation uses a different week for the switch from the MPS determined by the sales department to an MPS based on most recent realized sales. In fact we have performed simulations with the switch in week 4, 8, 12, 16 etc. until week 200. This last simulation, with a switch in week 200, is in fact identical to the reference simulation since in this run the MPS determined by the sales department is used for the entire simulation period.

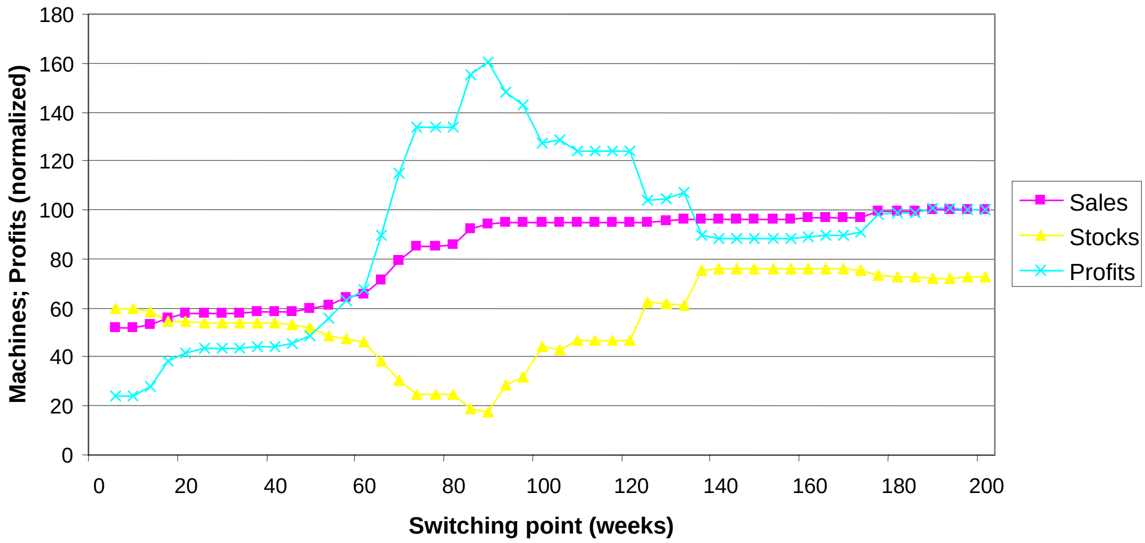

Figure 6: Normalized cumulative sales, end-of-life echelon stock levels and cumulative profits for different switching points between sales-driven and stock-driven SCC policies

Figure 6 reveals the following phenomena: During the first phases in the product life cycle, the sales department should indeed determine the MPS. This is shown by the low values of sales and especially gross profit that results if the switch is made before week 50. It is remarkable that, for this range of switching values, low sales go with high end-stocks. Apparently, although the system is not able to satisfy the high demand during the maturity phase, it still ends up with high stocks.

A sharp peak in total gross profit can be observed for switching values between 90 and 96. This is just at the end of the growth phase in the PLC. For these switching values the end echelon stock takes its lowest values. Apparently, for switching values in this range the supply chain has been best prepared by the sales department-driven MPS to take full advantage of the high demand during the maturity phase *without* ending up with excessive end-stocks in the supply chain.

For switching values larger than 100, we see that total gross profit sharply decreases to almost half of the maximum value, to increase a little but again for very high switching values. We also see that total sales continue to increase for higher switching values. This makes sense since the longer the sales department determines the MPS, the more machines become available to satisfy demand.

However, the relatively small increase in total sales that results from higher switching values is more than offset by the increase in echelon stock that remains at the end of the PLC. As a result, total gross profit sharply decreases if the switch from a sales department determined MPS to a stock-driven MPS is made long after the end of the growth phase. This is completely in line with our expectation as expressed in

Section 3. We may conclude that the lithography equipment manufacturer studied could have substantially increased gross profit from this product by using a PLC-driven SCC policy instead of its own sales department-driven SCC policy.

The above observations suggest that it is indeed important for equipment manufacturers with very short PLCs to switch at the right time from a sales department-driven MPS to an MPS that aims at controlling end-of-life echelon stocks. Moreover, the simulation results suggest that switching should take place in a rather narrow time slot around the end of the growth phase. The differences in gross profit are substantial; therefore it really pays to switch at the right time.

Conclusions

In this paper we have investigated the control of the supply chain for highly innovative capital goods by means of a case study of a semiconductor capital equipment manufacturer. Highly innovative capital goods are characterized by very short product life cycles and the lithography equipment manufacturer studied in this paper is very typical for this case.

This paper investigates the conjecture that, for products with very short PLCs, at some point in the PLC the supply chain control should switch from aiming at making as much as possible product available in the market to avoiding obsolete stocks at the end of the PLC. To investigate this conjecture we have developed a generic systems dynamics model of a capital equipment manufacturer supply chain, consisting of the final assembly phase, a subassembly phase, and two component manufacturing phases feeding both the assembly phase and the subassembly phase. The model covers materials, capacity requirements, materials and capacity availability, the effects of learning and quality feedback on capacity requirements and an MPS/MRP type of control system for the supply chain.

Using data from the lithography equipment manufacturer, the model has been calibrated to a part of the equipment manufacturer's supply chain. Using manufacturing, demand, planning and sales data of a recent new product, the calibrated model has been validated and calibrated to show output close to real-life data. This calibrated and validated model has been used to investigate the difference in performance between supply chain control based on a Master Production Schedule determined by the sales department, and a supply chain control policy where at some point in the product life cycle, control switches from being sales department driven to stock control-driven.

Our results show that, for the model of the capital equipment manufacturer used in this study, the gross profit for products over the entire PLC can increase with more than 30% if the switching point is chosen at the right point in the PLC, which appears to be at the end of the growth phase. Furthermore, the results show that switching too early leads to substantially lower sales and high end stocks, and switching too late leads to somewhat higher sales but substantially higher end stocks. Moreover, the results suggest that, due to the short maturity phase, these high gross profits are only obtained if the switch takes place in a narrow time slot around the end of the growth phase.

The results in this paper suggest a number of venues for further research. First, we may expect that also for products with longer PLCs an optimal supply chain control switching point exists. An interesting question is where in the product life cycle this point is located and how this position depends on the economic parameters of the problem. Secondly, there is the question how much the gross profit can be further increased by a more sophisticated supply chain control policy which is based on estimates of the shape of the remaining part of the PLC during the development of the PLC. Thirdly, there is empirical research into the question whether there are capital equipment manufacturers that actually use PLC–driven supply chain control policies, and, if this is the case, to investigate the characteristics of these PLC-driven supply chain control policies. The models and results in this paper provide a solid conceptual framework for these further research steps.

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