Screening Scenario-based Analysis of Modifications in Planning of Semiconductor Manufacturing

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***Abstract*— The current work discusses the results obtained from the screening analysis using a model that dynamically manages supply contract modifications. These changes are related to customer order patterns at the wafer fabrication stage and at a mid-term master planning level. A demand-driven two-stage model is used to depict the operations of a typical silicon foundry, in which the objective is to find the optimal economic production plan based on the existing customer base, demand profile, capacity utilization status, and modification patterns. The first stage finds the initial pre-production optimal distribution plan for manufacturing activities among the existing facilities over the entire planning horizon. In the second stage, the plan attained from the first model is reviewed and tweaked based on changes on demand (i.e. rescheduling or additional requests) or even production capacity. Therefore, new scenario-specific production plans over a shorter planning horizon are created. The aggressive customer due-dates and customer-specific production represents the main process conditions. Several scenarios for a case study are evaluated to assist with the development of the supply contract clauses.**

Keywords*— *Supply Contract; Production Planning; Two-stage Modeling; Semiconductor Manufacturing; Screening Analysis; Scenarios

I. INTRODUCTION

Since its formation, the semiconductor market has been characterized by several factors such as high market fluctuation, instability, and volatility. Rapid technological advances of semiconductors lead to short product life cycles, which confound market behavior. As the semiconductor firms are located far upstream in the supply chain, the variability in demand is created as a ripple effect from the downstream echelons due to the shift in the demand of the end-customers. Moreover, the semiconductor business operates globally while experiencing frequent up- and downturns. The instability of the semiconductor market requires a proper system of inventory management. Considering the short life cycle of the product, inventories should be kept to minimal to avoid product depreciation and eventual losses during a market downturn. At the same time, certain products should maintain enough inventories to satisfy high customer demands. Inventory managers must simultaneously consider the long lead time for certain products and potentially significant losses for not meeting customers' due dates [cf. 1]. Another important aspect of the semiconductor market is the expensive fixed assets; the fabrication facility ("fab") and its various tools. If a facility allows its machines to idle or if it makes the wrong product, the facility's wasted capacity leads to significant losses [cf. 2]. This capital-intensive industry requires making decisions at the right time when planning to build a new facility, to ensure the lowest possibility for an economic downturn during that period. Moreover, once the fab is running, the second goal would be ensuring maximized capacity utilization along with generating considerable revenues.

Referring to Figure 1, the front-end operations of wafer fabrication and probe are commonly carried out in highly industrialized nations, given the specifics and the profundity of these operations that take several weeks or months to be completed. Conversely, the back-end operations of assembly and final test are usually outsourced to countries with lower labor rates; processes at this stage do not require clean room facilities, and skills and expertise as the front-end operations and they can be rather completed in few days. Wafer fabrication is not only the most challenging task, but also it is the most capital-intensive semiconductor manufacturing operation. Fabrication of integrated circuits on wafers undergoes several hundred processing steps in several hundred unique expensive tools that have rather very short life cycle due to the fast evolution of the semiconductor technologies. Moreover, making the best use of these short-lifetime costly tools and exploiting their full capabilities remains a challenging issue [cf. 3].

The competition over the last decade has required companies not only to focus on designing good products, but also on manufacturing these products efficiently and cost-effectively. Many performance measures can be used to evaluate the manufacturing line; a primary measure is capacity utilization. As the initial investment to build and equip a new fab may reach several billion dollars, clearly machine utilization is critical. Other measures are the on-time delivery to customers, production yield and throughput, and production cycle time. Certainly, the goal is to keep these measures collectively predictive. Wafer fabs

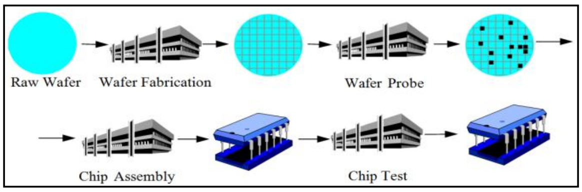

Figure 1. *Stages of Semiconductor Manufacturing [cf. 2]*

generally have a segregated production scheme, depending on the type of the product. Certain fabs produce high volumes of the most widely-demanded commodities, whereas other fabs specialize in producing a lower volume of application-specific ICs for a broad range of end customers. In both types of wafer fabs, the competitive market imposes a very quick response to any customer order; the goal is to meet the demand with the shortest and most accurate possible order lead time. A competent way for achieving better delivery performance and responsiveness is through the use of production planning. There is a great interest in using production planning tools because they offer more competitive advantages [cf. 4]. Historically, the cost reduction of the semiconductors was realized by mainly improving the physical aspects of the production, which have significantly contributed to productivity gains. Concurrently, there were also some efforts to enhance the operational processes within the wafer fab [cf. 5]. In fact, the chances of productivity gains from improving and developing the operational processes seem to be more promising and allow for better economic gains.

The goal of production planning is to find the best match between supply and demand. Such a goal usually occurs on the business-line level and uses the information of the allocated production quantities obtained from the capacity requirements plan. As far as master planning is concerned, it is run daily or weekly to respond appropriately to customer order confirmation within a typical planning horizon of 6-18 months. Confirmed orders are usually given higher priority over other supply reservations such as forecasts. Some regulations concerning inventory policies, sourcing strategies and resource utilization will translate into a set of soft constraints that balance the resource load across the available facilities. In other words, master planning tasks mainly deal with customer order confirmation, manage the inventory stocks, and release orders to the supply network [cf. 1]. Operational profitability of the semiconductor manufacturing sector is achieved with effective planning and utilization of available resources.

On the other hand, capacity planning usually falls under the long-term strategic planning, and decisions made include production capacity investments in order to meet long-term future demand, depending on several factors such as location of facilities, and product mixes. In fact, incorrect investments decisions can lead to huge; thus, sharing unconstrained demand forecasts and outsourcing of productions are widely adopted strategies in the semiconductor supply chains, to improve capacity planning and reduce the risk. Furthermore, due to the rapidly changing technology and often inaccurate forecast demand, on a higher granularity, semiconductor manufacturers face very high demand uncertainty. Even if capacity planning is performed and executed carefully, decisions to adjust or reconfigure production plan might be required during the execution stage; changes on demand can be also introduced even if the orders are realized and confirmed beforehand. The flexibility and modification options in supply contracts may allow customers to adjust their order quantities; either requesting to postpone their production, to adjust production quantities, or in worst case scenario to cancel the requests. Table 1 lists some of the common contract clauses used in the semiconductor supply [cf. 6]; this work focuses mainly on modeling the changes related to clause 3 (Cancelation), clause 2 (Quantity Flexibility) and clause 8 (Rescheduling), introduced in a mid-term time horizon and how should the production plan be altered to accommodate for the new changes introduced. The viability and the accuracy of these decisions can dramatically affect the profitability. The development of planning approaches to quantitatively address the ever-present uncertainties within the semiconductor production networks remains challenging, given the specifics of this industry. In the course of development of new planning and control approaches, the main objective of this work is to translate the results obtained from a production planning model into economic solutions for a foundry at tactical master planning level by capturing the dynamics of modifying supply contracts. The results can then be used for establishing or improving the supply contract terms and clauses.

II. LITERATURE REVIEW

In a review done by Geng and Jiang [cf. 7], the authors give a general review of capacity planning models in the literature. The section on mathematical programming methods includes comparisons between the Linear Programs LP) and Stochastic Programs (SP) and why SP models have developed and gained some popularity in this field. The SP usually models the uncertainty via scenario structures that could be either a two-stage or a multi-stage SP model. In the

TABLE 1- RANGE OF CONTRACT CLAUSES USED IN THE SEMICONDUCTOR SUPPLY CAHIN [CF. 6]

#	Clause	Description
1	Minimum Purchasing	This clause determines the minimum quantity of a product, which a customer will buy from a supplier. Common examples can be found in the high-tech industry, especially in the semiconductor industry, where a customer has to commit to a certain quantity because the supplier has to build up capacity well in advance
2	Quantity Flexibility	This contract clause allows one of the parties to deviate from an initially committed quantity. For example, a customer wants to change his previously committed purchasing quantity of a component because additional knowledge of demand has become available. How much and at what cost a supply chain partner can deviate from the initially quantity is determined by a quantity flexibility contract
3	Cancellation	The cancellation clause defines the customers liability in the case that the deviation of the updated demand information to the initially committed quantity is beyond what is defined in quantity flexibility and rescheduling contract clauses
4	Buyback/ Return Policies	With this contract clause, the customer can return unsold products to the supplier.
5	Allocation	The allocation clause specifies how the supplier's inventory is distributed among its customers when there is tight or insufficient supply compared to customer demand
6	Lead Time	With this clause, the lead time can be specified as either a fixed constant or a random variable.
7	Demand Signal	This contract clause determines the method and the granularity of the shared demand information between the customer and the supplier.
8	Rescheduling	The rescheduling clause defines the customer's flexibility to change the order quantity, to cancel or to reschedule an already confirmed forecast or order. Rescheduling means that the customer can prepone - or postpone forecasts or orders compared to the initial confirmed delivery date.

two-stage SP, decisions are made firstly with uncertainty involved: for example, with tool procurement plans. Then, in the second stage, the resource actions are taken to compensate for first-stage decisions once the uncertainty is disclosed. In the multi-stage SP, a revision of the capacity expansion plan is allowed based on the uncertainty revealed at each time period. As an example of the use of multi-stage SP in semiconductor application, Karabuk and Wu [cf. 8] present a scenario structure that incorporates demand and capacity uncertainty and uses a decentralized decision-making scheme.

Current approaches in the literature often focus on long-term capacity planning and short-term scheduling in the semiconductor industry. Mid-term master planning problems have been rarely attempted in the literature; many of those address the problem only generically. Ponsignon [cf. 9] develops the first master planning model using mixed integer program (MIP) that was solved using three different heuristic approaches. The model captures the operations of typical Integrated Device Manufacturers (IDM); thus, the option of subcontracting is also included in the capacity modeling to outsource production to external foundries if needed. The model distinguishes between in-house facilities and subcontractor foundries. In reference [cf. 10], the same model was solved using a commercial MIP solver and the results of some computational experiments are presented.

The model used for this current work was developed and built upon Ponsignon's model [cf. 9], providing an economic solution to mitigate the risk of demand variability in semiconductor manufacturing at master planning level, and capturing the impact of the dynamics of order modifications while taking industrial limitations and availabilities into consideration.

III. Model Overview

The base model of Ponsignon suggests a mathematical formulation with an economic objective function to be maximized along with demand satisfaction constrained by the available capacity. The model is able to regulate the wafer quantities to yield several products within the existing facilities over medium-term planning horizon. Refer to reference [cf. 9] for model formulation. The model used for the current work is an extension of the MIP, where the additional attributes includes production fungiblity factor, customer ranking, cost of capacity underutilization, and a second stage model. The extended model captures the operations of a foundry; thus, only in-house facilities are considered. Refer to reference [cf.11] for the extended model formulation.

The demand-driven two-stage mathematical model has an objective function that finds the optimal economic production plan subject to capacity availability and inventory constraints; the main decision variable is the completed wafers of multiple products in different facilities and time periods. Figure 2 depicts the model diagram of both stages. The first stage of the model finds the initial pre-production optimal distribution plan for manufacturing activities among the existing facilities over the medium-term time horizon (i.e. typically 6 months). The input demand to the first stage is based on the long-established customer orders and forecast demand of supply reservations. Changes in confirmed orders require a prompt response to the production deployment plan by initiating wafer starts or seizing an ongoing production if needed, considering the highly entailed manufacturing and inventory costs for the complex customized products that require long production cycle time (i.e., up to 12 weeks). In the second stage, the plan attained from the first model is reviewed and tweaked based on changes on either demand or capacity (i.e., due to machine breakdown) and therefore new scenario-specific production plans are created; additional decisions at this stage includes the option of in-fab inventory of WIP or scrap wafers for certain products. The overall model is capable to provide the optimal manufacturing setting based on the existing customer base, demand profile, capacity utilization status, and order modification patterns.

IV. Comutational Analysis

In this section, we describe some experiments performed and solved using GAMs software. We vary combination of several attributes once at a time and see the effect of each set of conditions on the overall performance. We conduct our tests for a time horizon of 24 weeks and fixed production cycle time of 8 weeks for 2 facilities and 3 customers, each having orders of two products. In Table 2, the characteristics of the products and the mixes at each facility are listed. From some preliminary comparative tests, factors that have been prevailing are chosen to be weighty but constant, such as modification time and intensity.

The tree diagram in Figure 3 shows the possible changes that could be realized in either the available production capacity or customer confirmed orders. Modification intensity is fixed to 50% for Customer 1 and 2 with changes

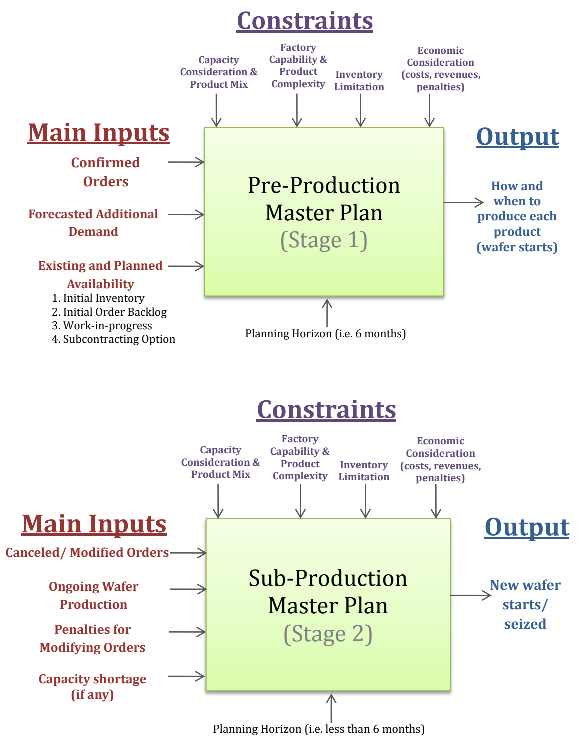

Figure 2. *Model Diagram of Stage1 (pre-production plan) & Stage 2 (the reviewed production plan)*

taking place in the 13th week of production. On the other hand, requests for additional products and total cancelation are only considered from Customer 3, and can take place from week 7 onwards. Initially, we consider orders from Customer 1 and 2, with a total of 4 products in the line. We perform tests for changes in single-product orders, one a time. This helps to first examine each item separately for a total of eight tests and then observe the changes when put into combinations. Subsequently, scenarios of all possible combinations of change in product orders, i.e., two products at a time, were examined. Then, each possible change in product order with capacity loss in its relative facilities was tested. Afterwards, we test extreme scenarios of capacity loss in both facilities with substantial change in orders of two products at once, both having decreased or increased requests. In the final set of tests, we consider orders from all the customers, with a set of 6 products, and we examine several combinations of modification requests from Customer 3 only. As for the key performance indictors used for the evaluation of the outcomes, we use: the change in profitability and in total confirmed and forecasts sales, the level of capacity utilization of facilities, and finally the total number of scrap wafers.

The results of initial comparative sensitivity analysis were performed by changing one factor at a time to evaluate the impact of modification instances. Adding products to the line seems to be the most promising scenario as an external factor of supply contract modification, especially if the new product mix offers better consumption the available capacity. Also, product complexity plays a role on this basis. Scrap wafers increase if the additional products are complex; as more intricate products requires more capacity compared to the less standard ones. On the other hand, the internal factor of capacity loss has resulted in the highest losses compared to other scenarios, as we don't only lose production volumes but also the capital investment put into the expensive state-of-the-art tools. Results suggest that the time of modification is the most crucial factor and can lower the profit dramatically. Another significant factor is the modification intensity. If the quantity is lowered with a small percentage, the change can be coped with easier than extreme cases as cancelation. Table 3 lists the percentage change in profit with respect to the level of changes in either

TABLE 2- PRODUCT CHARACTERISTICS: SCREENING ANALYSIS

Products	Belonging to Customer	Product Type	Product Demand	Production Facilities
Product A	Customer 1	Complex	Medium	F1
Product B	Customer 1	Complex	Increasing	F1
Product C	Customer 2	Standard	Medium	F1, F2
Product D	Customer 2	Standard	Increasing	F2
Product E	Customer 3	Standard	Medium	F1, F2
Product F	Customer 3	Standard	Instable	F1, F2

modification time or intensity. We can see that for scenarios of decreasing order quantities or additional product requests; the later the change, the less profit gains. These numbers along with other strategic factors could be translated into contract clauses to set certain levels and time periods for possible modifications.

Another but less influential factors are the demand of the product of decreased or canceled requests and the ratio of work-in-progress for future requests with respect to the backlogged quantities. The higher these attributes for a modification instance, the more the scrap wafers are and the less the profitability is. We also have observed that standard products from the least complex group (ex. similar to commodities), shows more dynamic and less impact with respect to orders reduction. These products can be manufactured in many locations, the reduction in their production volumes has less effect on the utilization level of different facilities and their partial absence in the line offers manufacturing capacity for other backlogged products.

As far as the current screening analysis is concerned, we tested several instances of combinations of changes introduced either in product orders or production capacity. Complexity of the products as well as the instability of its demand aggravate the modification instance and eventually are translated into profit losses. For the product mixes manufactured in the two facilities, there were some extra production quantities for the work-in-progress, as present demand didn't allow for full utilization of resources. This justifies the large quantities of scrap wafers realized for each modification instance, especially for the complex medium-demanded product in the most upgraded facility. Products sharing several facilities offer better utilization of resources and production flexibility. For example, if there is decreased orders for a product in facility A and increased orders of a product in facility B, a product sharing both facilities will balance the production volume and offset this change.

Afterwards, we tested the impact of losses of capacity along with changes in orders; the losses were larger and surge with further capacity loss. The situation is eased a bit, when products are of lower demand and in distinct facilities experience the change. We also tested scenarios of adding products in the seventh week of production and canceling the orders afterwards in a later week of production. As the

TABLE 3- AVERAGE CHANGE IN PROFIT WITH MODIFICATION FACTORS

Factor	Time (for each one week delay in modification)	Intensity (for each 1% change)
Decreasing Order Quantity	-1%	+2%
Requesting Additional Products	-2%	+0.1%
Production Capacity Loss	+1%	-1%

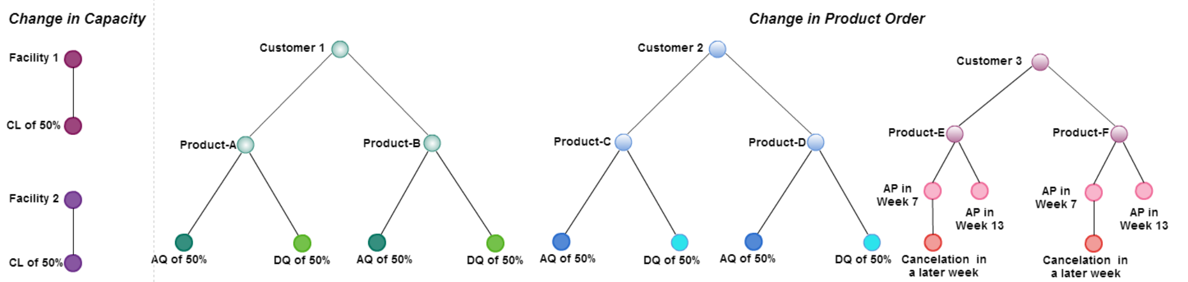

Figure 3. *Tree Diagram for Possible Scenarios (CL: Capacity Loss, AQ: Additional Order Quantities, DQ: Decreased Order Quantities AP: Additional Products)*

gap between addition and cancelation increases by one week, profit decreases with an average of 2% for this specific case study.

V. CONCLUSION

The current work has considered analyzing the results obtained from a mathematical model that captures foundry operations and finds the optimal setup for the production plan by accommodating the uncertainty in demand. Results suggest the significance of proper capacity planning using forecast tools in order to achieve uniform distribution of production requests when restrictions and fabrication complexities are present. For instance, since the analysis was carried out for a set of randomly generated controlled data, we had a capacity overrun. Moreover, the capacity planning should be done in parallel with the revision of contract clauses to ensure that customers commit to their orders and at the same time to limit the possibilities for modifications that could lead to huge losses. The results of the both sensitivity and screening analyses assess in forming the contract clauses to ensure the least losses with respect to possible changes in orders.

As for future work, application of this kind of analysis to real case studies will eventually provide more focus on the results, making them appropriate for the specific production setup. The model could also be used for further analysis with regards to the existence of dynamic bottlenecks which restrains the capacity and affects the product mix as well as the overall fab utilization rate.

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