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Scenario Modeling in Demand-Constrained Semiconductor Supply Chains

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Abstract

Semiconductor supply chains operate within highly complex, globally distributed networks that are often constrained by volatile demand, limited capacity, and technological dependencies. Scenario modeling serves as a critical decision-support tool for navigating these uncertainties, enabling stakeholders to simulate and evaluate alternative strategies across various constraints. This review paper examines a comprehensive range of modeling approaches including capacity planning simulations, inventory optimization frameworks, behavioral modeling, and technoeconomic assessments, all applied within demand-constrained semiconductor environments. Drawing on ten significant academic sources, the paper emphasizes how scenario-based analysis aids in enhancing responsiveness, resilience, and strategic alignment in supply networks. Particular attention is paid to allocation strategies, imperfect quality impacts, sense-and-respond systems, and discrete-event simulation. Through the integration of financial, operational, and behavioral variables, scenario modeling emerges as an essential framework for managing uncertainty and improving supply chain performance in the semiconductor industry.

Keywords: Scenario Modeling; Semiconductor Supply Chains; Demand Constraints; Inventory Optimization

1. Introduction

Semiconductor supply chains represent one of the most intricate and critical logistical structures in modern globalized production systems. Their complexity arises from a mixture of long production lead times, high capital intensity, sensitive demand dynamics, and deeply interconnected global networks. Within this context, demand-constrained environments pose unique challenges, as they significantly impact production planning, allocation, and inventory optimization. Modeling various scenarios in such constrained systems becomes essential for maintaining operational resilience and maximizing resource efficiency.

This review explores the literature and methodologies on scenario modeling within demand-constrained semiconductor supply chains. The primary focus is on understanding key strategies, simulation frameworks, inventory optimization techniques, and behavioral dynamics that are utilized to handle uncertainty and complexity in such networks. Particular emphasis is placed on how different modeling approaches, frameworks, and decision rules are used to navigate demand fluctuations and ensure supply chain performance. The paper draws from ten key scholarly references, addressing scenario modeling through conceptual, technical, and empirical lenses.

2. Foundations of Semiconductor Supply Chains and Demand Constraints

Semiconductor manufacturing operates within a tightly coupled supply-demand network that demands rigorous synchronization across various stages of production, from wafer fabrication to final assembly. The characteristics of such networks are multi level networks which comprised suppliers, foundries, back-end manufactures and OEMs. The

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subsequent effects of the disconnections of demand can be larger further up the chain, due to the lead times that are involved, and the capital-intensive manufacturing.

General knowledge of the supply-demand network to be run on is possessed, and the knowledge of it is basic before going further to the scenario modelling. Supply-demand network concept involves a network of interdependent processes/ nodes that are oriented to fulfill some particular end-user requirement in a joint production/ distribution. A supply chain of semiconductor is characterised by a complex structure which includes long cycle times, erratic yields, erratic demand and frequent limited capacity in the products. The networks have to be efficiently run within the demand constraints and this is only possible through implementing the forecasting, planning and implementation strategies within a responsive and adaptive system [1].

Representation of such environment requires the modelling of the limitations of the environment such as the production capacity, demand-fulfilment obligation and the logistics lead time. These factors should be featured in the sophisticated models with an aspect of diversity of products and customer requirements. These dynamics will be operationalized by the creation of computational tools and simulation models that will be able to define the finer dependencies of the stages of production to the demand indicators [1].

3. Capacity Planning Under Demand Volatility

Balancing of the global capacity is one of the primary issues of semiconductor supply chains that occurs under the circumstances of demand variability. Capacity planning needs to consider high fixed cost, low production flexibilization and inter-product- line sharing of resources. This skill of quick and accurate decision-making in the capacity planning is a competitive edge in those situations when the demand is small.

The simulation models provide the platform of analysis of the various capacity planning options. As an example, the semiconductor production systems behavior in the real-life can be simulated with the assistance of the discrete-event simulations and enable the planners to test the demand conditions and the way they influence the capacity consumption. An example of an international semiconductor company can be studied to find out how the location of capacity bottlenecks and seeking alternative ways of production can be done in case of simulation. The volatility of demand influx modelling companies may make contingent plans when the demand is high in the quarters and would therefore make the most appropriate decision regarding the investments in either plant expansions or subcontracting [2].

Also, scenario based simulation enables organizations to compare the outcomes of the decentralized and centralized planning organization structures. To illustrate, centralized planning model may ensure enhanced coordination on regional levels and minimize overcapacity and enhance responsiveness of a supply chain overall in the situation where the degree of uncertainty of demand is high. Alternatively, the less centralized models would be more responsive on the local levels where the environment is not as unpredictable. They are based on the modelling of various demand and supply with the foundation of system wide simulation environments which make rational decisions in case of uncertainty [2].

4. Resilience and Adaptation in the Face of Disruption

The global supply chains in semiconductors are vulnerable to shocks in the world, e.g. pandemics, geopolitical tensions, or natural disasters. In these situations, system risk and resiliency strategies are to be included in scenario modelling. One can make use of the recent COVID-19 pandemic as the example of how the mismatches of demand and supply may spread in the industries with catastrophic production and distribution failures.

As a survival tactic, semiconductor supply chains ought to adopt adaptive strategies, which are pre-modelled and scenario simulation. Such strategies can be divided into four, namely, bridging, buffering, agility, and collaboration. Continuity of supply is accommodated by use of alternative access of the suppliers or the logistics paths. Buffering involves the maintenance of spares or reserve power. Agility is characterized as the redistribution of resources in a dynamic manner, on demand and collaboration is an activity that deals with a joint-planning and risk-sharing activity among associates [3].

In this scenario modelling of case, trade-offs of such strategies are determined in variable levels and duration of interruption. An example is that it is under simulations that the size of a buffer to be used in sustaining the levels of services at a given disruption probability can be determined. Alternatively, the effect of the agility mechanisms like shipment re-routing or the cross-training of the workers on the recovery times can be modeled. These establishments point to the fact that scenario modelling cannot be described as a planning tool, but also a mechanism to build resilience in semiconductor supply-chains [3].

5. Allocation and Customer Prioritization in Demand-Limited Environments

The demand induced limit supply chains in semiconductor will entail customer priorities and assigning orders. The decisions made in allocation directly affect the customer satisfaction and association with the long term customer as well as the revenue. The allocation strategies can be investigated regarding the allocation scenario modeling to examine the impacts of various rules on the performance of the entire supply chain.

Some of the allocation models, as a suggestion, will assign the customers the highest priority of profitability, or a contract, or precision of forecast. During high demand seasons where there is a shortage of supply, companies would need to make choices on how much inventory to allocate to individual customers and the amount of inventory to allocate. A simulation model can be used to analyse the effect of these allocation rules that will show a trade-off. Short term is good as it wants to focus on the high-margin customers but is destructive to such a partnership in the long term with smaller clients. Alternatively, the forecast-based allocation can be used to encourage the clients that make decisions on good demand forecasts and this creates a self-strengthening planning environment [4].

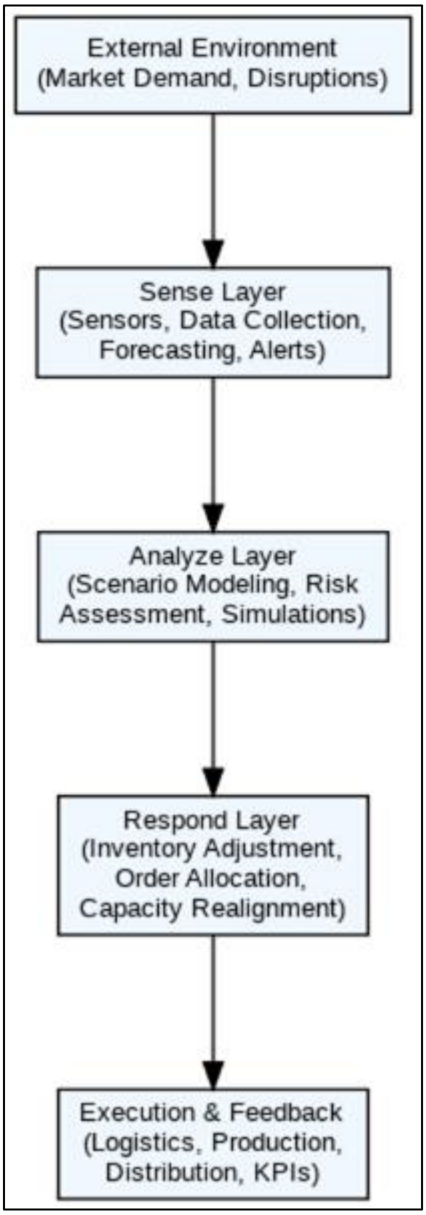
The allocation strategies involved in the scenario modeling give us the insight of the impact of various policies in the overall performance of supply chain. This is attributed to the fact that in work with simulations, one can experiment with different customer portfolios, product mixes, and demand patterns and, therefore, companies can develop sensible and equitable allocation systems [4].

6. Sense-and-Respond Frameworks for Dynamic Decision Making

The conventional models of planning are relatively rigid in terms of the environment. Nonetheless, this dynamic character of the demand of the semiconductor requires the presentation of real-time adaptive schemes. The sense-and-respond strategy helps the supply chains to be informed about the diversion of the scheduled demand or supply conditions and reacts on the dynamic basis.

The strategy is comprised of scenario modeling and predictive analytics and real-time monitoring integration. Sense component entails the procedure of obtaining information on sales, production and external sources to compute the possible disruption or spikes in demand. A respond component then establishes pre-programmed processes, including re-order routing, changing the production plan or reassigning inventory. It is based on the scenario models, which allow the planners to model an unlimited number of contingencies and how they are impacting supply chain KPIs [5].

Digital twins may also be supported in semiconductor industry with the aid of scenario modeling. Digital twin refers to the Internet depiction of a real-life supply chain system that has the capacity to replicate the effect of the real existence of changes in real-time. These models can help the companies to continuously examine the viability of other response strategies in diverse demand and supply situations. It allows the making of superior and faster decisions in which the market is volatile [5].



Source: Adapted from [5]

Figure 1 Sense-and-Respond Framework in Semiconductor Supply Chains]

7. Inventory Optimization and Financial Forecasting in Scenario Modeling

The core components of the scenario modelling of the demand-constrained semiconductors supply chains are the optimization of the inventory levels. The inventories buffers would offset the unpredictable demand yet too much inventory in the inventory is a waste of capital and the product life cycles are extremely short that they may lead to obsolescence. Hence, the scenario modeling should be moderate as much as possible between services and financial constraint and product lifecycle.

Financial risk data embedded in inventory optimization techniques, predictive variation and lifecycle analytics have become more popular in semiconductor settings. Inclusion of these dimensions in the scenario planning model would help the firms to have better trade off between the depreciation of the assets and stock-out risk and the cost of holding. The volume based metrics are not the only metrics that inform the models of a financial informed but also the revenue at risk and the implications of the cost-of-capital are taken into consideration. These models are modelling the uncertainty in demand that contains the stochastic parameters and policies testing of which comprises dynamic reorder point, time phased inventory allocation and dynamic just in time replenishment [6].

These parameters can be used to do the scenario modelling such that the companies can test various inventory control policies with various demand shapes and scenarios of supplier reliability. The outputs will also give an impression on the most suitable level of buffer, reorder level and the lowest level of accuracy of the forecasts it makes that will ensure that the operations are carried out as a smooth running process. An example can be used to prove this by showing how the minimization of the error in forecast by 10 percent can lead to the minimization of safety stock by 7 percent, and the reduction of carrying costs hugely. This explains the necessity to be precise in planning systems particularly in cases when many nodes are incorporated in an international semiconductor system [6].

8. Imperfect Quality and the Newsvendor Problem in Semiconductor Modeling

Along with the changeable demand, there is also uncertainty regarding the quality that affects the supply chain in terms of the performance. Variation in the quality of output in semiconductor manufacture is usually divided because the manufacturing process is complex due to the lack of consistency of the material used in manufacturing and in the tools. When a constraint of supply in the case is not limited by the capacity alone but also by the ideal quality, scenario modeling must make the adjustments to the yield rates and rework possibility.

One of the models that are famous in this regard is the Newsvendor problem that balances the cost of excess stock holding and the cost of low stock holding within a one period environment. Newsvendor can be tweaked to faulty rates and unspecified quality in real semiconductor supply chains. The classic model can be simulated using a quadratic representation of the conventional model to extrapolate the occurrence of the total cost at varying defect probability and the optimal order quantities might be determined [7].

The assistance of this model to simulate the scenario, perhaps, will enable the planners to decide the effect of imperfect quality on inventory requirement, level of service and profitability. An example of such condition is that, a 10 percent defect situation can be indicative of a large optimum order quantity when compared to a perfect quality situation particularly on a high-margin semiconductor product. Any small changes in the quality assumptions can cause tremendous change in the cost-optimal inventory decisions as illustrated in Table 1 [7].

Table 1 Cost Impact of Imperfect Quality in Semiconductor Inventory Decisions

Defect Rate (%)	Optimal Order Quantity (Units)	Expected Overstock Cost ($)	Expected Stockout Cost ($)
0%	10,000	5,000	3,000
5%	10,526	5,600	2,700
10%	11,111	6,300	2,500

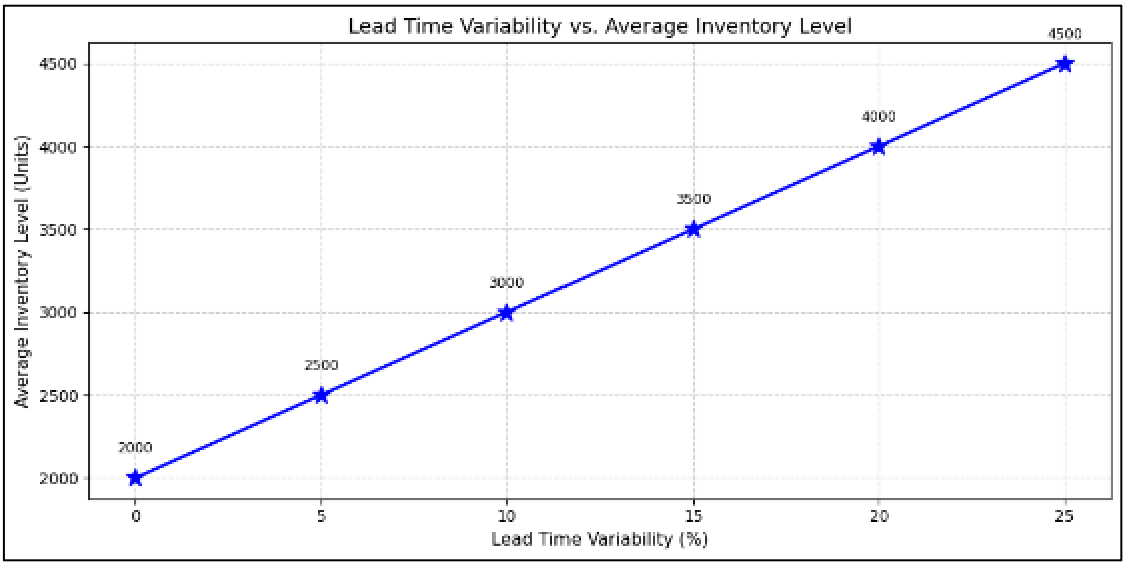
Source: Adapted from [7]

9. Replenishment and Discrete Simulation Modeling

A second area of significant need of demand-constrained supply chain is replenishment modeling, especially of parts and raw materials in multifaceted semiconductor process. The discrete simulation models provide the computational capability and resolution to model and examine the replenishment operations in various situations of need and lead times.

The stochastic dynamics of part replacement like variable supplier lead time, manufacturing delays and consumption rate across the factory floor can be computed using a discrete simulation based model. The models permit scenario analysis of replenishment policy, such as kanban loops, minimum-maximum system and periodic review strategies. By changing the input variables, such as the forecast accuracy, the reliability of the vendor or the transportation times, the decision-makers can simulate the outcome of the changes in the level of stocks, service rates, and the measures of costs [8].

Performance measures used to display simulation outputs are performance measures such as fill rate, inventory turns, and backlog days. Taking an example the following graph shows how the variability of the lead time influences the average level of stocks when there is a constant demand. The high reliability of the upstream supply nodes to guarantee inventory efficiency is associated with the rapid increase in inventories with an increase in inventory variability with the increase in the lead time [8].



Source: Adapted from [8]

Figure 2 Impact of Lead Time Variability on Average Inventory Levels

10. Technological Advances and Material Constraints in Modeling Scenarios

The technological limitations also determine the manner in which the supply chains that are associated with semiconductors carry out scenario modeling. Notably, the move towards thinner silicon substrates in photovoltaic and microprocessor systems has implications on supply base, price framework and defect opportunities. An example of such conditions is the limited availability of materials such as ultra-thin silicon or rare-earth elements in the manifestation of the demand.

The systematic method of assessing the possibility of using such materials is presented by technoeconomic scenario modeling. These are the analysis of the situations with various price projections, manufacturing capacities, and adoption. Thin silicon may prove to be both cost- and efficiency-effective in semiconductor, but trade-offs in both fragility and yield losses and equipment requirement have been found by scenario model analysis. The sensitivity analysis models come handy in determining the break even levels at which the losses in forms of yield can be offset by cost savings through material reduction or equipment upgrades [9].

This form of modeling would come in handy when it comes to making capital investments especially when the demand is unknown or policy changes are about to occur. As an example, the demand of thinner wafers could be stimulated by policies that demand sustainable production when the production of such wafers can be more complicated. The scenario analysis also enables the planners to introduce changes simulating regulations, economic and technologies in like manner, which helps in optimization of long term strategic decisions [9].

11. Behavioral Modeling and Forecast Incentives

Traditional scenario models often assume rational and informed actors. However, human behavior and decision-making introduce variability that can affect demand planning accuracy and responsiveness. In integrated semiconductor supply chains, behavior-driven errors such as over-forecasting, panic ordering, or passive forecasting can cause severe supply chain distortions.

Behavioral modeling introduces bounded rationality into scenario simulations, reflecting how planners and sales teams respond to incentives, uncertainty, and system feedback. For example, a behavioral rationing model examines how different forecasting incentives impact order quantities. When forecasters are incentivized based on forecast accuracy, they tend to moderate their estimates. Conversely, if allocations are based on forecast quantity alone, exaggeration becomes a rational strategy [10].

In scenario modeling, incorporating such decision rules allows simulation of real-world forecasting dynamics. The results often show that aligning incentives with performance metrics reduces volatility and improves order accuracy over time. These behavioral elements are especially important in demand-constrained environments where every unit of allocation matters and over-committing inventory to unreliable forecasts can result in opportunity costs [10].

12. Conclusion

The utilization of scenario modeling to demand-constrained semiconductor supply chains takes the central role in enabling organizations to address the alterations of demand, constrained supply, technology, and behaviour inconsistencies. Examples of tools and techniques to deal with complexity and these are just the identified ones among the literature reviewed and it goes without saying that there exist numerous other frameworks and methods among the sense-and-respond frameworks and capacity planning, as well as technoeconomic analysis.

The combination of discrete simulation, financial modelling, quality variability and behavioural analytics is a complete solution to a problem that provides an overall indicator of the decision in semiconductor related scenarios. By simulating various demand scenarios as well as the impacts of these downstream, supply chain professionals will be in a position to prepare to embrace uncertainty, improve service delivery and make sure that the operational strategies are aligned to the business objectives.

In the opinion that the semiconductor industry remains a changing terrain, especially after the global turmoil and shift in technologies, scenario modeling will remain inevitable in an attempt to make it resilient and competitive.

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