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RESEARCH OPPORTUNITIES REGARDING TREE AND NETWORK PRODUCT STRUCTURE REPRESENTATIONS IN A SEMICONDUCTOR SUPPLY CHAIN

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ABSTRACT

Semiconductor manufacturing is highly complex, invest intensive and constantly changing due to innovation. The semiconductor product market is highly volatile due to short product life cycles with difficult-to-predict ramps and end-of-life demands. These challenges are mitigated via flexible production capabilities, e.g. dynamic routing or rescheduling, used by planning systems to transfer volatile demands to well-utilized factories. The product structure is one of the keys for enabling the desired result. Product structure representations include linear, tree, and network. In this paper, definitions of several product structure representations are given and hypothesized benefits and drawbacks are discussed. Research questions are posed, current research efforts are introduced, and the hypothesis that a time dependent network-tree representation would be beneficial is postulated. The problem statement is explained by a real case merger where risk and opportunities based on the choice of product structure representation were relevant and no final solution was determined.

1 INTRODUCTION

Due to various production and market factors, flexibility is required in semiconductor manufacturing supply chains. However, the increased complexity associated with this flexibility must be effectively managed to leverage the benefits that flexibility provides. Production factors contributing to the need for flexibility include high lead and cycle times as well as variable quality factors (Mönch et al. 2017). Market factors contributing to the need for flexibility include demand volatility and bullwhip effects (Chen et al. 2013), short product life cycles (Ehm and Lachner 2019), and a high rate of innovation (Chen et al. 2017).

Complexity concerns that arise from increased flexibility are also rooted in production and market factors. It is not uncommon for a single semiconductor product to be partially manufactured in multiple factories around the world, including the use of subcontractors to complete manufacturing steps (Chen et al. 2008). Ensuring seamless flow of semi-finished goods and raw materials from one site to another is one complexity resulting from a more flexible supply chain. Market constraints such as government trade policies or customer specific exclusions become more difficult to manage in a supply chain with increased flexibility. Planning processes and data may need to be augmented or altered to provide the level of traceability required to meet market constraints.

The typical production processes of semiconductor manufacturing include wafer fab, probe, assembly, and final test. Wafer fab and probe are usually called front-end processes and have long cycle times. Assembly and final test are called back-end processes and have shorter cycle times. Typical factors affecting the supply chain include uncertainty with respect to quality and short product life cycles. To effectively cope with and mitigate the factors impacting the supply chain, semiconductor manufacturers employ a variety of strategies concerning design of the supply chain and its supporting processes. These measures include make to stock versus make to order operations, wafer- and die-banks, and customer order decoupling points. Common support processes include planning processes that affect procurement, production, distribution, and sales on a short-, mid-, and long-term basis (Mönch et al. 2017).

In this paper we introduce product structure representations and their impact within the semiconductor supply chain, based on empirical evidence. We then discuss the advantages and impacts of several representations in SSCM (Semiconductor Supply Chain Management). We summarize related literature on the semiconductor-related product structure representations. Finally, we discuss our current research efforts and possible research questions for academia, and we formulate a new possible product structure representation to be investigated.

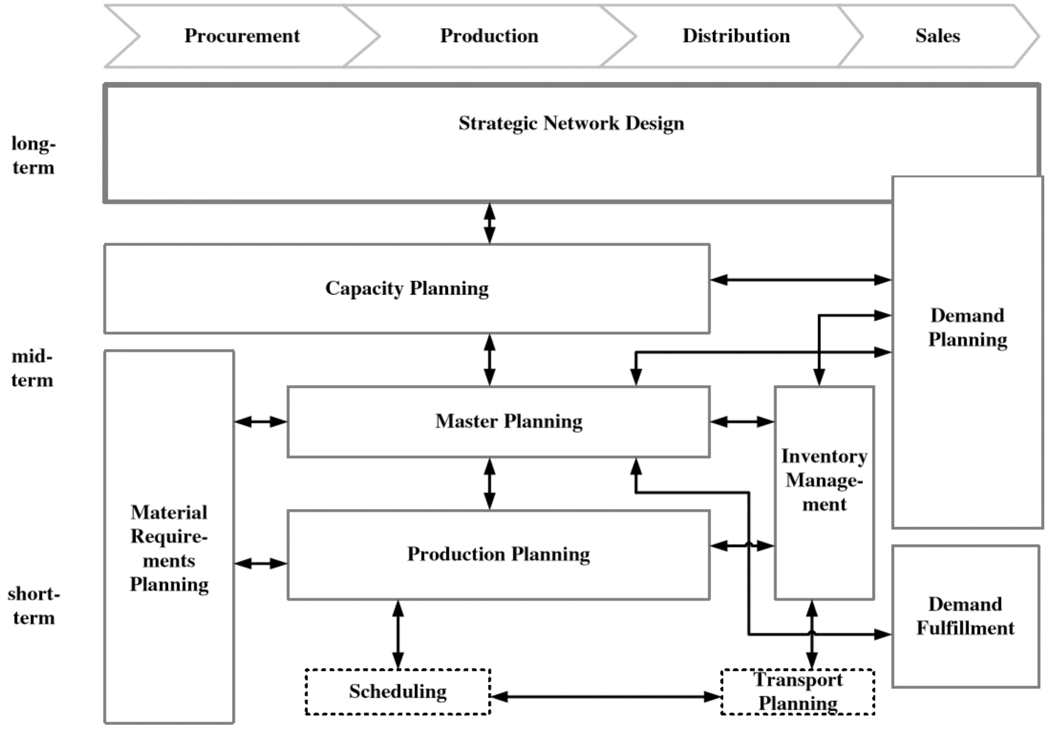


Figure 1: Typical supply chain processes in the semiconductor industry (Mönch et al. 2017).

1.1 Overview of Semiconductor Supply Chain Processes

To understand the impact of product structure representations on the semiconductor supply chain, we present an overview of its common processes as described by Mönch et al. (2017). See Figure 1. Strategic network design and planning concern themselves with answering long-term questions like what strategies best fit the company and what needs to be implemented to enable those strategies. Demand planning focuses on forecasting demand with varying degrees of aggregation as well as understanding forecast uncertainty. Inventory management deals with determining what, if any, safety stocks are necessary in the supply chain and where they should be located to minimize risk. Capacity planning determines additional equipment requirements to meet a certain demand and also what can be produced with current equipment. Master planning and production planning, which are most important for this paper, seek to determine planned production and inventory quantities based on inputs from the capacity and demand planning. An important part of master and production planning is being able to effectively handle demand fluctuations and the allocation of limited capacities. Material requirements planning (MRP) ensures production sites have the necessary materials to execute master and production plans. Demand fulfillment handles the tracking of orders and includes order promising, setting due dates, and planning shortages.

1.2 Product Structure Representations in the Semiconductor Industry

An important factor affecting the complexity management of flexible supply chains is the way product identifiers are defined and utilized within supply chain processes and data. The definition of product identifiers and product structure representations within a company's data structures and processes does not constitute a change in the production plan, only a change in how the information contained in those structures is grouped and utilized to perform different functions.

One way of identifying products in manufacturing industries is using Bills Of Materials (BOM). In certain cases, a BOM also includes a structured multilevel list including information on manufacturing operations, material required for production, and other important manufacturing information. In the semiconductor industry, two types of BOMs are commonly utilized. We introduce the Product-BOM (P-BOM) which contains the planned sequence of manufacturing operations for a given product and the Operational-BOM (O-BOM) which contains in addition necessary information to perform manufacturing activities for a specific operation (e.g. required leadframe and glue for die bonding in BE manufacturing). Potentially thousands of O-BOMs exist for similar operations due to minor changes resulting from location, equipment, or component to be processed. For each manufacturing step in a P-BOM, there is a corresponding unique O-BOM. See Figure 2. Using these BOMs, higher granularities of product identifiers capturing information on raw materials, locations, and work routes of the complete manufacturing of a semi-finished or finished product can be defined. These identifiers are used in semiconductor supply chain processes and their supporting data.

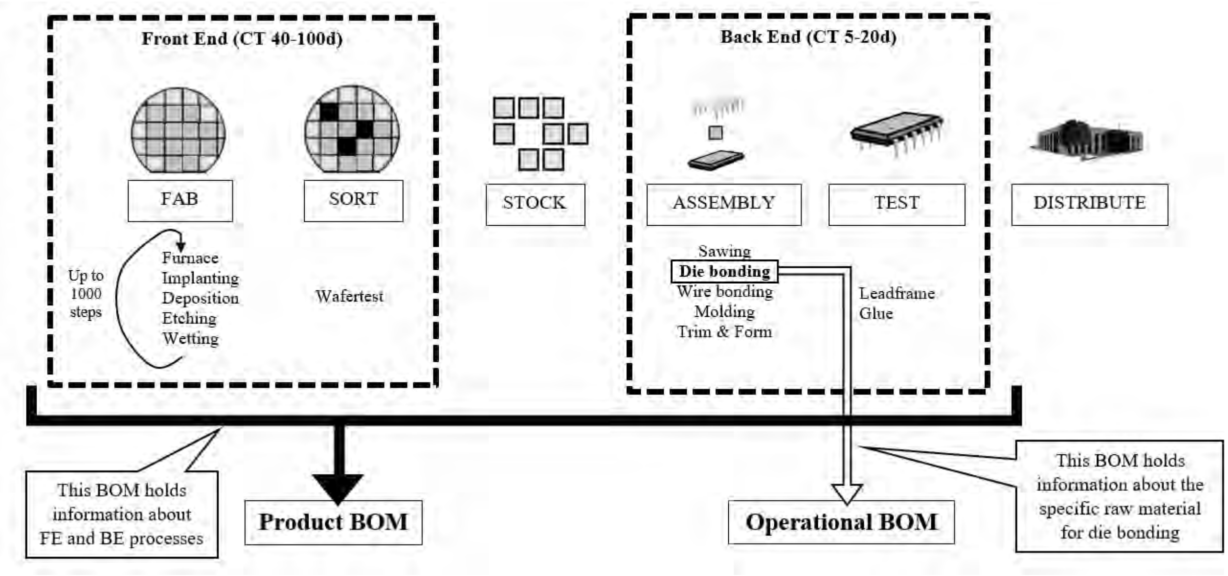


Figure 2: BOM structures in the semiconductor manufacturing process.

We define the decision to use a specific product identifier for a specific process (manufacturing or supply chain) as a product structure representation. In other words, a product structure representation is the data representation of the planned sequence of operations (production routing) taken from a P-BOM as well as the manufacturing activities at each individual operation taken from the O-BOM. The choice of representation has an impact on different levels of planning (demand constraining, stock evaluation, internal shipments, etc.). One such example occurs in master planning. Master planning neglects information contained in the O-BOM for the purpose of generating a feasible plan, due to the number of O-BOMs and the information they contain. To compensate for this, material requirements planning (MRP) ensures that O-BOM constraints are met based on the optimized plan generated by the master plan in a separate process.

Three examples of product structure representations in the semiconductor industry are bamboo (or linear), tree, and network representations. See Figure 3. The bamboo representation is not discussed, as its lack of flexibility makes it impractical for further use in the semiconductor industry. Instead, we will concentrate on the more flexible tree and network representations.

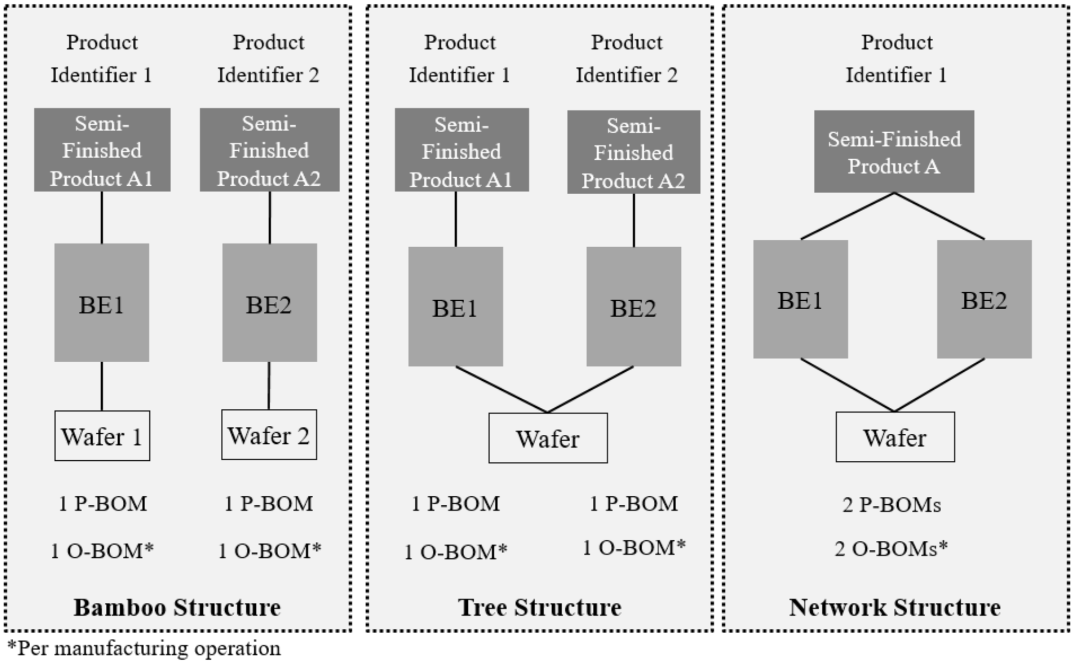


Figure 3: Example of product structure representations in the semiconductor industry: bamboo, tree and network *(BE stands for back-end manufacturing processes).*

In a tree representation, a planning product identifier is defined by a change in activity or component that still corresponds to the same semi-finished or finished product. This means that in a tree representation, a planning product identifier corresponds to only one P-BOM. An example of this would be if two identical semi-finished goods (e.g. a wafer) undergo the same process but in two different locations, they would each have a different product identifier. Similarly, if two similar and interchangeable semi-finished goods (e.g. wafers) undergo the same process in the same location, they would also have different product identifiers. See Figure 3.

In a network representation, the planning product identifier is defined by all activities or components that correspond to the same semi-finished or finished product. In a network representation, the planning product identifier corresponds to multiple P-BOMs. For example, if two similar and interchangeable semi-finished goods (e.g. wafer) undergo the same process in the same location, they would have the same product identifier. Similarly, if the two identical semi-finished goods undergo the same process, but in two different locations, they would also have the same product identifier. See Figure 3. Product structure representations and their product identifiers have a large impact on supply chain management because they form the basis of supply chain processes and data.

2 LITERATURE REVIEW

Degbotse et al. (2013) explains how IBM represented product structures to optimize their supply chain planning. Optimization of planning systems proves difficult because computational constraints limit the ability to implement sophisticated optimization techniques. Furthermore, planning based on computationally cheap heuristics is not suitable for the complexities of the semiconductor industry. IBM tackled this problem by deconstructing product BOMs. BOMs were separated into complex and simple portions for each major step in manufacturing, as well as for alternate supply routes for the same product. The deconstruction of the BOMs allowed the complex portions to be solved by a mixed-integer program and the simple portions to be solved by linear programs. The separation of the BOMs reduced the amount of tasks to be solved by the mixed-integer program, making its use computationally feasible. As a result, IBM was able to improve capacity utilization, customer service, and stock levels. This paper shows how the representation of the product structure in planning systems enables optimization of the semiconductor supply chain.

Leachman et al. (1996) discusses how Harris Corporation implemented a new planning system after an acquisition to improve on-time delivery performance. It should be noted that this paper was written during the earliest stages of globalization and with only 30 factories on two continents. After the merger, manufacturing of certain products from one company needed to shift to a factory of the other company. However, Harris Corporation and the acquired company utilized different systems and data for their supply chain processes. This mismatch negatively impacted on-time delivery performance during the integration of the companies. Harris decided to implement a new planning system to improve the on-time delivery performance. The choice of a network representation of the product structures in the planning data was central to the project's success. Ultimately, the new planning system drastically increased the on-time delivery performance for the company. Significant efforts and time were invested in change implementation and management to ensure the necessary level of data quality and completeness for implementation. These efforts included development of specialized processes, tools, and interfaces for individual production sites to ensure standardization across the entire supply chain. The changes implemented were high impact, expensive, and took a long time to complete, but were deemed necessary due to the critical condition of Harris's business scenario.

3 PROBLEM STATEMENT

The way product structure representations aggregate information contained in P- and O-BOMs affects supply chain processes. In a tree representation, product identifiers correspond to a single P-BOM, and therefore have only one O-BOM per manufacturing operation. In a network representation, product identifiers correspond to several P-BOMs, and therefore have many O-BOMs per manufacturing operation. One impact of this is that, for a tree representation, the MRP system knows all subsequent manufacturing operations and corresponding material requirements once production begins. In a network representation, the MRP system does not know all subsequent manufacturing operations once production begins because the subsequent operations can come from any number of different P-BOMs and therefore have different O-BOMs. In cases of high demand uncertainty and fluctuation, master planning has greater flexibility in the network representation, as planning can change the subsequent operations to optimize based on free capacity. However, if the plan fluctuates with high frequency, the MRP system is unable to ensure that the site that will perform the operation has the necessary material to execute the plan. Without additional mitigation processes or tools, this would result in lost capacity at the site and a late product delivery to the customer.

It is clear that switching representations in a company's processes and data (possibly due to a merger or acquisition) requires a mindset change across the entire company. Consider again the example mentioned above regarding MRP in a network representation, but for a company which is switching from tree to network representation. Such a company would have to rethink the way their master and production planning systems and MRP systems work together in order to mitigate the possibility of capacity losses and lateness and reap the benefits of increased flexibility.

The focus of this paper is to illustrate research opportunities in the use of product structure representations in the complex semiconductor supply chain. The solution to this problem does not reside solely in listing the theoretical advantages of one representation compared to the others, but in determining the best representation to implement within a company's supply chain data and processes and when (e.g. tree in front-end and network in back-end or tree under given market constraints).

3.1 Company A and B Merging Challenges: Tree and Network Cohabitation

Company A developed its product structure representation based on its choices of IT software for supply chain planning. Improvements and changes to the supply chain and IT planning system were implemented under the boundary condition of using a tree representation. Therefore, all the reporting tools, planning algorithms, stock management, and other processes were optimized to support trees.

Company B, which was acquired by Company A, chose to balance the need for flexibility and complexity through the use of a network product structure representation. The network representation offered Company B increased flexibility, but also came with additional complexity. One such example was that Company B was sometimes unsure of the provenance of a semi-finished good until it had arrived at a stocking point, and, more importantly, some usually non-problematic BOM materials were not available due to sudden route changes induced by variable planning. Company B developed specific systems and manual processes to mitigate these issues.

It was decided that the joint company would continue to use Company A's IT and data systems, but augment those systems and data to support Company B's networks. This decision was made in the interest of minimizing the required large scale changes and negative impact to both companies. The data structures supporting all supply chain processes and tools in Company A had to be enhanced because the existing data structures didn't support networks. Supporting networks and trees meant adopting a new way of thinking for both parts of the newly joined company. An illustration of this is that with bamboo and trees, there is no sourcing decision, as a change in location implies a new product identifier. Company A had to introduce the new concept of deciding the source of products based on new parameters (e.g. priorities, locations, etc.) into their data and IT systems. An additional example came from the reporting of demand and supply for Company B. Reporting for Company B after the merger was difficult because the environment used by Company A wasn't designed with networks in mind. One could argue that Company A should have adopted Company B's IT systems, but it is impossible to truly know the implications of attempting to utilize Company A's tree representation in Company B's environment, which was optimized for networks.

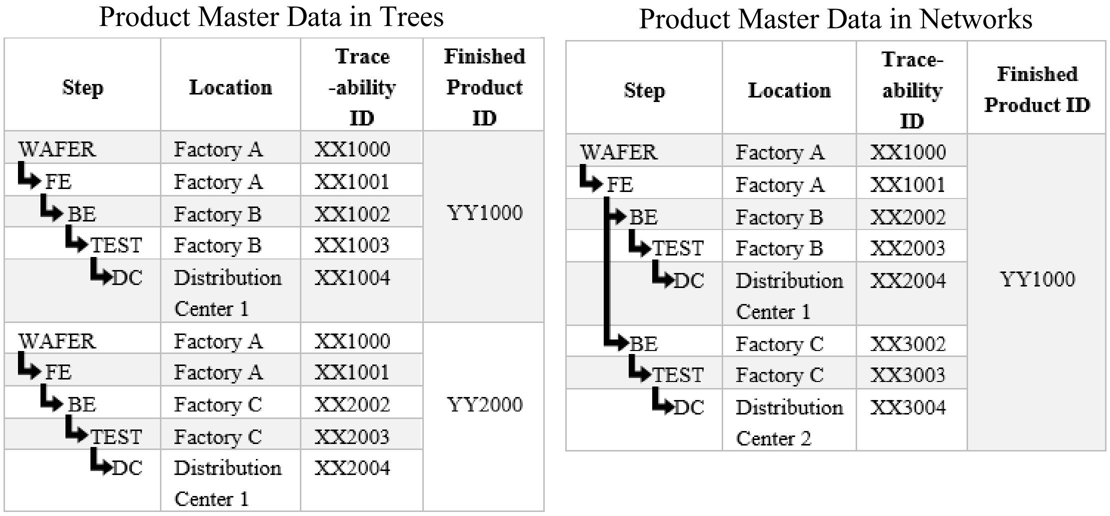
The joint company successfully created an environment where network and tree representations could coexist within Company A's IT and data systems. However, the unique circumstance of acquiring a company with such a markedly different product structure representations posed the fundamental question: which representation should the joint company utilize going forward?

3.2 Hypothesized Benefits from Both Structures

To help illustrate the pros and cons of the product structure representations listed below, Figure 4 shows an example of a basic chip product structure in tree and network, with corresponding product IDs and routing. In this example, a chip goes through BE in two different factories (B and C), which implies the creation in tree representation of two product identifier with their own branches. In Network representation, even with a change in routing, the product identifier stays the same.

The main advantage of networks compared to trees is the flexibility in the routing. For trees, the routing is blocked when the front-end production starts. This means that if the planning system decides to send the product to a certain location for the back-end process; the die will inevitably end up at this location, unless there is a manual change. This way of working is not a problem in industries with short cycle times. However, for the semiconductor industry, high cycle times imply that once the route is blocked, it will be for the next four to twelve weeks. If there are changes or uncertainties in the demand or problems at a manufacturing site, there could be a misalignment between the customer orders and the actual planned demand. In theory, the network product structure solves this problem by adapting the route to the best option during short term changes in the demand.

Another advantage of networks is the reduced number of product identifiers. With the trees, one route results in the creation of a new unique identifier; meaning that the product the customer orders could be one of many possible identifiers. For the networks, it is only one identifier. Fewer planning product identifiers means less computing time for planning. It is also the case in the order management process, where the system will run availability searches for every product identifier.



Product Master Data in Trees

Step	Location	Trace-ability ID	Finished Product ID
WAFER	Factory A	XX1000	YY1000
↳FE	Factory A	XX1001	
↳BE	Factory B	XX1002	
↳TEST	Factory B	XX1003	
↳DC	Distribution Center 1	XX1004	
WAFER	Factory A	XX1000	YY2000
↳FE	Factory A	XX1001	
↳BE	Factory C	XX2002	
↳TEST	Factory C	XX2003	
↳DC	Distribution Center 1	XX2004	

Product Master Data in Networks

Step	Location	Trace-ability ID	Finished Product ID
WAFER	Factory A	XX1000	YY1000
↳FE	Factory A	XX1001	
↳BE	Factory B	XX2002	
↳TEST	Factory B	XX2003	
↳DC	Distribution Center 1	XX2004	
↳BE	Factory C	XX3002	
↳TEST	Factory C	XX3003	
↳DC	Distribution Center 2	XX3004	

Figure 4: Example of a product´s master data in tree or network approach.

Trees have a reduced level of complexity when it comes to MRP as the route is fixed and known when production begins. This ensures back-ends will have sufficient time to order any necessary raw materials, reducing lateness and increasing capacity utilization. Additionally, trees make it easier to handle regulatory or customer induced exclusions in the supply chain. Since the production planning under a Tree is route specific, it is easier to understand where a product is coming from, and where it will be going.

Due to the complexity of systems affected by the product structure representations, it is impossible to evaluate their efficacy through rationalization alone. It is hypothesized that theoretically networks are better in every way compared to trees. However, the specific constraints of the semiconductor supply chain and market mean the theoretical advantages need to be balanced with the complexity of implementation in reality. Simulation and other evaluative methods must be used to adequately assess the impacts of the product structure representations on a company and define conditions for when a certain representation should be used over another, as well as to provide insight into the best route forward and potential impacts of these representations with respect to mergers and acquisitions.

4 RESEARCH OPPORTUNITIES

It would seem that the network representation of the product structures is always better from a theoretical point of view, but, in the real case merger discussed in this paper, the network representation created challenges with respect to materials planning, on-time delivery, and traceability. Constraints on the semiconductor supply chain grow more complex each day. More research needs to be conducted to answer some of the following questions: Of the different product structure representations (e.g. tree and network) available, how does a company determine which is best for them? How well can the representations handle semiconductor supply chain constraints (e.g. import and export restrictions, materials lead-time, etc.)? Would it ever make sense to use multiple representations simultaneously across different product lines, geographical regions, or other divisions? Would it make sense to implement a structure that is time dependent? Do the answers to these questions change when considering a no-touch planning system versus a planning system supported by humans? Answering these questions requires the use of evaluative methods more concrete than simple rationalization, namely simulation.

4.1 Proposed Methodology: Discrete-Event Simulation

Simulation models can reproduce real life behaviors of product structure representations and help determine conditions where one representation is more advantageous than others. Simulation models can attempt to confirm the hypothesized benefits of the different representations with consideration of real constraints, determine in which business scenarios a network or tree representation is better suited, and explore the feasibility of new representations such as a time-dependent network.

The prerequisite of such studies is to determine what a simulation model can do and cannot do for the given case. The steps of creation for a semiconductor supply chain simulation library are described in a review by Ehm et al. (2011) and for ad-hoc simulation models by Law (2015). There are basically three main methods for simulation modeling: system dynamics, discrete-event modeling, and agent based modeling (Borshchev 2013). A suitable method for product structure representation related simulation model is discrete-event based. A discrete system is one for which the state variables change instantaneously at separated points in time at which an event occurs (Law 2015). This is how the planning algorithms used in the semiconductor industry work.

Before starting to build a simulation model, the first step, specifically in the semiconductor industry, is to determine the appropriate level of simulation (described in the discrete-event simulation tutorial for semiconductor facilities by Fowler et al. (2015). See Figure 5). A simulation model for product structure representations will likely focus on the third level of simulation, the internal supply chain.

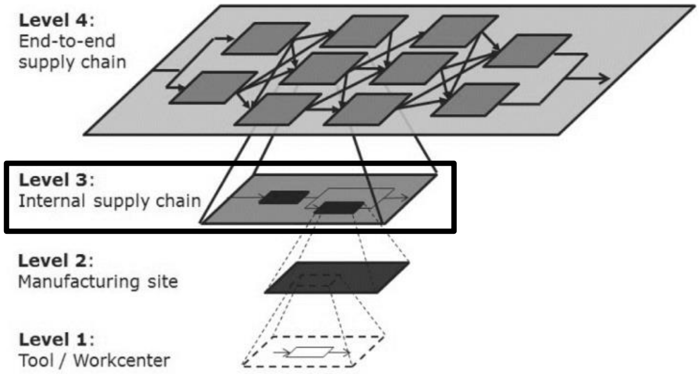


Figure 5: Four levels of simulation in semiconductor manufacturing (Fowler et al. 2015).

The second step is to determine the required level of detail (Law 2015): full detail (Jain et al. 1999), reduced (Ewen et al. 2014) or atomic (Duarte et al. 2002). Two approaches are possible, because of the dynamic nature (e.g. demand depending on forecast) of the model inputs: reduced and atomic. Suitability of the two levels of detail needs to be assessed on a case-by-case basis. The implications of a reduced level of detail are delay times defined in the input data for most of the processes (front-end, back-end, etc.). For atomic level of details some parameters and demand generation may be based on dynamic probability distributions but further studies will be needed to determine adequate real data based on distributions.

The verification and validation steps according to Balci and Whitner (1989) should be followed. Key performance indicators, e.g. capacity utilization or runtime, must be monitored to compare the performance of the product structure representations. The simulation model can be used to analyze multiple performance metrics as described by Buckley and An (2005). Finally, as the simulation will be based on a demand horizon specific to the semiconductor industry, the setting of an optimal number of replications and elimination of the warm-up must be conducted following the recommendations of Hoad et al. (2010) and Law (2008).

4.2 Current Research Efforts

We are currently experimenting with discrete-event simulations to model the impact of network and tree representations on master, production, and material requirements planning, capacity utilization, and product lateness. We are also attempting to model the impact of network and tree representations on the runtime of master planning and demand fulfillment systems. We are particularly interested in evaluating the feasibility of a time-dependent network approach in hopes of achieving a best of both worlds solution. In a time-dependent network, demand would be planned like in a traditional network until a specified number of weeks before the demand is due, called the frozen fence. Frozen fences effectively firm master plans and are currently implemented in semiconductor supply chains when production starts or a week earlier to enable detailed production planning. See Figure 6. This frozen fence could be applied to the product identifiers used in planning and thus the network demand will be planned like a tree within this frozen fence, creating a time-dependent network. This could help to mitigate the loss of capacity or stock due to raw material shortages resulting from variability in MRP under a fully network representation.

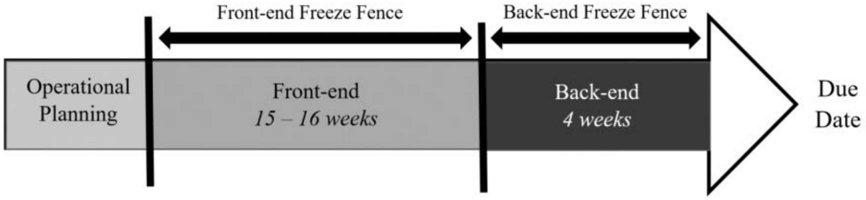


Figure 6: Typical frozen fence in the semiconductor industry, which limits the planning flexibility for operational planning, but enables needed stability for manufacturing.

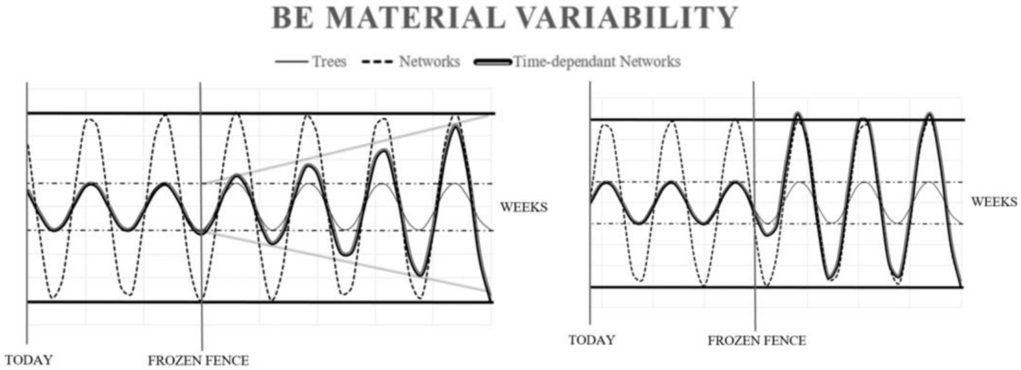


Figure 7: BE material variability for trees, networks and time-dependent networks.

Figure 7 shows the variability of raw material required for back-end production under a tree, network, and time dependent network. Under a network representation, the change in necessary stock levels of materials to enable back-end production is much greater than under a tree representation. This is due to the inability of MRP systems to support the routing fluctuations from the master planning system on such short notice. The plans issued are less stable under networks than trees, therefore the MRP system is unable to truly know how much material is needed at a specific site. Depending on when or how much the routing from the production planning system changes, it might be impossible for the MRP system to ensure there is sufficient material at the production site. This results in lost capacity and lateness. From an MRP perspective, the less variable the production routing, the better. However, from a production planning perspective, route flexibility is of great advantage. A time-dependent network which locks the product routing at a specified time (defined by an extended frozen fence) could allow production planning to have greater flexibility than in a pure tree environment, while limiting the BE material variability with sufficient time to order necessary materials, solving the MRP problem. One research question is to determine how to transition from the network to the tree, and if the transition occurs progressively in time (funnel approach or damped harmonic oscillator with low damping ratio – left graph on Figure 7), is bluntly stopped right before the frozen fence (very high damping ratio - right graph on the Figure 7), or other approaches.

Another challenge in addressing the tree versus network problem is finding a balance between complexity management, performance improvements and the impact on current processes by comparing the improvements to key performance indicators (e.g. back-end material availability, lateness and capacity utilization) with the required necessary changes for a given company. The data compatibility of the different structure representations between two companies plays a key role. Data structures, ideally, should enable network and tree representations and support the transition between SP (Sales Product) and FP (Finished Product) levels, as described in Figure 8. If companies participating in a merger or acquisition use different representations and cannot support the other company's representation in their data structures, high impact changes will be required to enable their integration.

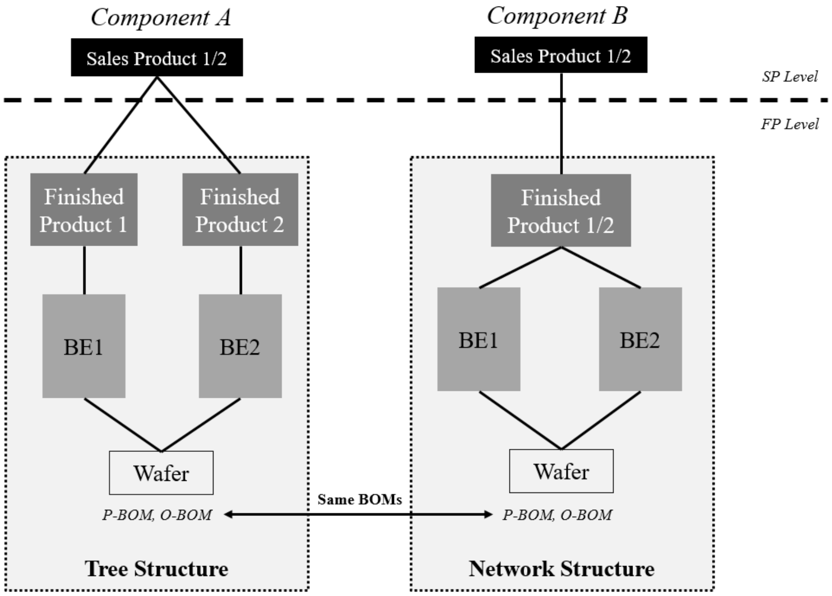


Figure 8: Data structures and how product structure representation influences the relationship between FP and SP level: the same products (SP1/2) come from the same P-BOM and O-BOM but with different structure representations (tree and network).

4.3 Future Research Opportunities

In general, additional fundamental research needs to be conducted regarding the impact of the O-BOM and product structure representations on supply chain processes in the semiconductor industry. The existing body of literature for supply chain simulation in the semiconductor industry considers the information contained in a P-BOM. We could not find any literature covering the O-BOM levels of information in semiconductor supply chain simulation. Discrete-event simulation is well suited to investigate optimal implementations of different product structure representations (tree or network) across the supply chain of a semiconductor manufacturer. More studies should be conducted to evaluate the impact of product structure representations under various customer ordering behaviors and business situations on more supply chain and supply chain adjacent processes. Simulations studying how well a product structure representation performs when tested against a variety of conditions by observing the impact on supply chain KPIs would have great value to the semiconductor community. The goal of such efforts would be to define a range of operability for the different representations, which could serve as a decision tool for semiconductor manufacturers going forward. Furthermore, simulation could help to define new product structure representations such as the time-dependent network solution or other hybrid representations and determine if these representations should be dynamic or static for a given business situation.

Simulation techniques should also be applied to study the impact of product structure representation changes in a company due to mergers and acquisitions. Mergers and acquisitions are becoming more and more common in the semiconductor industry, and differences in product structure representations between entities have a large impact on companies during and following an integration. This is evidenced by the merger discussed in this paper, where serious efforts were undertaken to integrate a network and tree representation under an existing IT infrastructure. Leachman et al. (1996) illustrates how this incompatibility can have an extremely negative impact on a company's business and how resolving such incompatibilities requires large amounts of time and financial investment to correct. Simulations investigating the impact of changes in product structure representations under different IT and data environments could inform companies when considering the feasibility of potential mergers or acquisitions.

5 CONCLUSION

The product structure representations derived from P-BOMs and O-BOMs were introduced. The problem concerning product structure representations was explained via a real case merger where significant efforts were made to support network and tree representations under an IT system initially designed only for trees, but a switch to a single representation was not made. A brief overview of hypothesized advantages and disadvantages of trees and networks was given. Current discrete-event simulation efforts to answer fundamental research questions regarding product structure representations were introduced. These efforts include studying the impact of trees, networks, and time-dependent networks on master planning, production planning, MRP, and demand fulfillment. Additional research opportunities relating to the semiconductor supply chain and product structure representations were also introduced.

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