

Analysis of a customer demand driven semiconductor supply chain in a distributed simulation test bed

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Abstract – Effective supply chain management (SCM) enables organisations to be more competitive in the current world of global manufacturing by reducing costs and improving the quality of customer service. Simulation can assist in moving towards these goals by evaluating the feasibility of alternative policies for managing a supply chain. However, simulation of multiple factories within the supply chain, with a high level of granularity in particular, can be very complex and computationally intensive. In this paper, we describe how a distributed simulation test bed enabling very detailed supply chain simulation can be used to study a customer-demand driven semiconductor supply chain.

Keywords: Distributed Simulation, Semiconductor Manufacturing, Supply Chain Management

1 OBJECTIVE AND INDUSTRIAL SIGNIFICANCE

In today's increasingly globalised markets, manufacturers are permanently forced to look for ways to sharpen their competitive edge. These efforts can no longer be limited to the four walls of a factory but need to be extended to the entire supply chain [1,2]. Manufacturers need to ensure that their operations integrate well into the supply chain so that products can reach the end-customers efficiently and cost-effectively. The need to have a competitive supply chain is particularly critical in the semiconductor industry, due to the large capital investment and the high value of end products [3] which have a short market life-span because of rapid changes in technology [4].

This calls for SCM, which involves planning and managing the flow of material and information through multiple stages of manufacturing, transportation and distribution. SCM involves multiple echelons, processes and organisational functions that coordinate and integrate together [5]. It includes inventory replenishment as well as planning of operations at each manufacturing stage. It also includes planning of shipments for products from one stage to the next. SCM can help manufacturers to maintain high utilisation of equipment with minimal inventory while improving customer service performance and profitability.

Since supply chains are often large systems consisting of many entities interacting in complex ways [6] managing a supply chain and finding the right strategy across the supply chain is a challenging task [7]. Hence, analysis tools and methodologies that can help in managing a supply chain efficiently are increasingly important [8]. Two basic categories of approaches can be identified for managing supply chains: solution evaluation and solution generation [9]. The first category deals with evaluation of the possible configurations of a supply chain design whereas the second generates an optimal configuration for a given set of objectives. This paper focuses primarily on solution evaluation.

Among various tools and methodologies, discrete event simulation has been proven valuable as a practical tool for representing complex interdependencies, evaluating alternative designs and policies, and analysing performance tradeoffs for supply chain systems [10,8,1-2,11-12]. Simulation allows both material and information flow to be modeled through each of the stages in the supply chain, together with complex decision logic for planning, scheduling and control. In addition, simulation can handle stochastic demand patterns and environments, multiple criteria and objectives, etc.

The popularity of using simulation in managing supply chains is also reflected in the literature. For example, IBM developed a supply chain simulator, which comprises a mix of simulation and optimisation functions, to model and analyse its own supply chain issues [13]. IBM also used its own simulation-based supply chain analyser to visualise and quantify the effects of making changes on a hypothetical supply chain, and the impact of the changes to the system performance [14]. [2] described a solution methodology for supply chains based on an integrated simulation and optimisation approach [15]. [16] described a simulation study on the supply chain for a large logistics operation. The results indicate that improvement in forecast accuracy can provide larger savings than process automation changes. The paper also pointed out the usefulness of simulation to evaluate the performance of supply chains.

The need for executing supply chain simulations based on a full-detail model has also been pointed out: [3] compared two models of different level of detail for semiconductor manufacturing supply chains. In their paper, it is shown that simulations incorporating

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detailed models are required to determine the correct inventory levels for maintaining desired customer responsiveness. Abstracted models can give inaccurate results that may subsequently lead to erroneous decisions. Reference [2] drew similar conclusions in their paper. They used multiple models with varying degrees of detail representing the same supply chain. It is shown that the system dynamics vary with increasing detail in the model. It is concluded that a strategy found to be the most effective on an abstract model is not always the best for a detailed model. In another paper [3], it is stressed that high-fidelity simulation is required for optimisation of planning and execution of supply chains.

Simulation enables evaluation and analysis of complex systems such as those found in semiconductor supply chains, but as the model increases in size and realism, a more powerful simulation capability that is beyond the sequential execution approach is required. The High Level Architecture (HLA), which is a framework developed by the Defense Modeling and Simulation Office (DMSO), provides the necessary infrastructure for large-scale distributed simulation. In HLA, a federate can be viewed as a component simulation model that is taking part in a large simulation [4]. A federation consists of a set of federates. In the case of supply chain simulation, federates can be factories in the supply chain and the federation is then the supply chain itself. In our work we have adopted this infrastructure in a distributed simulation test bed to improve on the simulation execution speed, to support reusability of existing simulation models and interoperability between different simulation packages. Applicability of distributed simulation for decision-making in semiconductor manufacturing has been demonstrated by [17].

In this paper, we describe the simulation test bed and report on the results of analysis for a semiconductor supply chain using the test bed. The next section explains the supply chain simulation model used for the study. Section 3 describes the simulation test bed. Section 4 discusses the experiments that we performed using the test bed and their results, followed by the conclusions in Section 5.

2 SEMICONDUCTOR SUPPLY CHAIN MODEL

The simulation model used in our study comprises the basic elements of a supply chain [3]. These elements include manufacturing, transportation, business processes and customer orders as depicted in Fig. 1. Two successive stages of material transformation, from a wafer fabrication facility to an assembly and test facility, are modeled. The wafer fabrication facility is the supplier to the assembly and test facility, which subsequently supplies Integrated Circuits (ICs) to end-customers. The transportation of wafers between the two manufacturing stages and the transportation of ICs to customers are modeled as well. Fore-

casting, production and inventory planning that are related to business processes are incorporated in the model. Customer orders are generated with the actual rate allowed to be different from the forecasted rate so as to simulate real life situations.

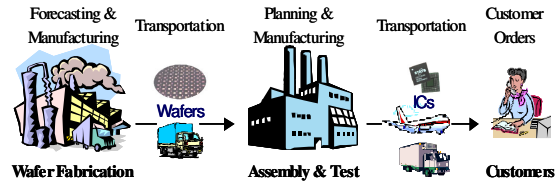


Fig. 1. Scope of the semiconductor supply chain.

The wafer fabrication plant data is based on factory data from Sematech dataset 1, which is available through the Internet [18]. The data for the assembly and test facility is based on past projects with the industry. The data, particularly volume release and factory capacities, has been adapted to ensure that the production quantities and the utilisation of facilities are consistent with what is typically found in the industry. In our supply chain model, the production of wafers in the wafer fabrication facility is based on a make-to-stock strategy driven by forecast, whereas the production of ICs in the assembly and test facility is based on a make-to-order strategy. The volume release rate of wafers is varied periodically (i.e. weekly, bi-weekly, monthly, etc.) based primarily on the forecasted demand and the availability of wafers in the supply chain. The lot release in assembly and test facility is driven by actual customer order arrivals. For further details, refer to the paper by [3].

The major components in the supply chain model and the interactions between them are summarised in Fig. 2. In the supply chain, the federates interact with each other through information and material flow. The information flow is shown using dashed lines while the material flow is shown using solid lines. There are four federates in the supply chain:

1. Demand Generator (D/G) – Customer order generator
2. Lot Allocation Engine (LAE) – Order planning
3. Wafer Fabrication (W/F) – Wafer fabrication facility
4. Assembly & Test (A&T) – Assembly and test facility

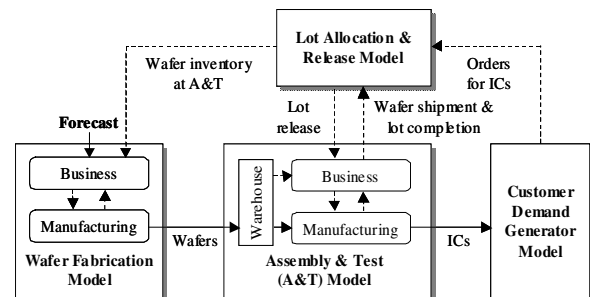


Fig. 2. Interactions between components of semiconductor supply chain.

Both the W/F and the A&T factory have a business process and a manufacturing process. The manufacturing process simulates the transformation of raw materials into products while the business process simulates production planning and inventory management. The model currently simulates two types of wafer products, and each of these products is used to manufacture two different types of ICs (i.e. a total of four types of ICs) in the A&T facility (see Table 1).

Table 1. Scenario considered in the supply chain model.

A&T Product (IC)	A&T Order Size	Wafer Lot Size	Die Per Wafer	Wafer Product
P1	21660 ± n%	≤ 24	200	W2
P2	20660 ± n%	≤ 24	210	W2
P3	20830 ± n%	≤ 24	200	W1
P4	20875 ± n%	≤ 24	200	W1

The D/G generates customer orders for each type of IC on a daily basis. These orders are fed to the LAE, which then assigns and releases orders to A&T based on the availability of factory capacity and wafer inventory in A&T. Fabricated wafers are shipped to the A&T warehouse on a daily basis with a shipment delay of a day. The wafers in the warehouse are used to produce ICs in the A&T facility, and the completed and packaged ICs are transported to customers with another day's delay. A more detailed description of each federate is provided in the following subsections.

2.1 Demand Generator (D/G)

The D/G generates customer orders daily based on a pre-defined demand profile for each type of ICs. The volume for the orders of ICs can be varied each week by altering the demand profile. Each order is randomly assigned to a customer and due dates are randomly assigned to each customer order, based on a uniform distribution. The order information is sent to the LAE daily with a one-day delay (i.e. to simulate daily planning in the LAE).

2.2 Lot Allocation Engine (LAE)

The LAE receives customer orders from D/G, plans the orders in standard lot sizes and subsequently sends the lot release information to A&T for the actual release of the product into the factory. In the order planning process, two major issues are involved. The first issue is to allocate A&T factory capacity to the orders (i.e. capacity planning), and the second issue is to assign wafer lots available in the warehouse of A&T to the orders. The order planning procedure is adapted from the lot-to-order matching policies described in the papers by [19] and [20]. We have extended the matching policies to deal with multiple products for our supply chain model, instead of single product policies as depicted in the papers. The planning procedure is as follows:

1. **Order Prioritisation:** The heuristic dynamically

ranks and prioritises orders accumulated on a given day based on a function of the order size, its lateness, the customer priority and the product priority.

2. **Ranking of wafer lots in decreasing lot size:** Lots for each wafer product in the warehouse of A&T are ranked in decreasing order based on the lot size.
3. **Allocation of factory capacity and assignment of wafer lots to orders:** For each customer order in the ranked list, the factory capacity and the wafer lots are first checked for availability to satisfy the order requirement. If both the capacity and the wafer lots are sufficient for the requirement, the order will then be allocated and assigned with the capacity and the wafer lots respectively before it is released into the factory. The actual size of a released order will always be greater than or equal to that of the actual customer order size due to the lot-to-order matching policies. The additional ICs produced in the order are termed Die-To-Warehouse (DTW) inventory
4. **Release of A&T orders in standard lot sizes:** Orders are released into the shop floor at regular intervals based on standard lot sizes. Each A&T product has its standard size as provided in Table 1. The lots that complete all the A&T process steps are accumulated to reform the original orders. The completed orders are then sent to customers.

2.3 Wafer Fabrication (W/F)

As mentioned earlier, the W/F is represented by a Sematech data set and produces two wafer products, which go through 210 and 245 process steps respectively. There are 32 operator groups in the dataset. The primary dispatching rules for machines are FIFO and Setup Avoidance (only in medium and high current implantation machines). Wafers processed in the W/F are then sent to an inventory hold in the A&T. A transportation delay of 1 day is required for this shipment. W/F releases wafer lots into production based on the product's work-in-progress level in the factory and in transit, inventory level of the wafer product in the warehouse of A&T, the desired safety stock level and the forecasted demand of the product. Adjustments to the release quantities in the W/F are based on the inventory updates, which occur at fixed time intervals and can be weekly, bi-weekly, monthly, etc. Wafer releases can be summarised by the following formula:

1. **Wafer release quantity** = Forecast demand – Excess inventory

Where

2. **Excess Inventory** = \sum (Work-in-progress in W/F, WIP in transit, Wafers remaining) - \sum (Safety stock level, and Cumulative demand from current to target period)

Also,

3. **Wafer remaining** = Wafer inventory in the A&T - Wafers required for all 'unplanned' orders.

The cumulative demand is computed based on the sum of the forecast demands from current period to the target period. The number of periods in the summation is dependent on the average cycle time of the product considered. The stated wafer release formula is slightly different from the version found in the paper by [3]. In our formula, we have introduced safety stock level and considered wafer inventory shortage. The yield loss during wafer production process has also been incorporated into the forecast.

2.4 Assembly and Test (A&T)

The A&T dataset has four products and each product has approximately 25 process steps. A&T receives lot release commands from LA and releases lots based on the pre-determined release times and sizes determined by LA. The major dispatching rule for machines in A&T is FIFO.

3 SIMULATION TEST BED

The simulation test bed used for this study is an HLA-based discrete event simulation system that originated from a semiconductor supply chain simulator developed in C++ under a joint project between Singapore Institute of Manufacturing Technology and the School of Computer Engineering at Nanyang Technological University, Singapore [3]. The test bed is implemented using the Run Time Infrastructure (RTI), which is an implementation of the HLA Interface Specification [4]. In our model, each sub-model of the supply chain maps to a federate in the supply chain federation. Each federate in the federation is executed on separate process in workstations and can be geographically distributed.

Since the supply chain model is developed modularly using the HLA, it is straightforward to replace any federate with a new one as long as the interface format standard is adhered to. In our test bed, we have made the demand generator and production planning separate federates so as to realistically simulate what is commonly happening in industry. In semiconductor manufacturing supply chains, the locations of customers, planning centers and manufacturing facilities can be geographically dispersed. Another reason for making them federates is to later replace them by commercial tools in a 'plug and play' manner.

Parameter files are used to define the overall scope of the distributed simulation. In addition, each federate has its own parameter files for defining the specific configuration of the federate in the supply chain. The parameter files for the federate can be used to define dispatch and setup rules for each machine set, priority of products, weekly demand profile, safety stock level, and so on. The factory federates also have the Sematech format files, which are used to specify process routes, resources such as machines and operators, resource unavailable times such as down times and break-times, and volume release of products.

As the simulation of the supply chain starts from an empty factory condition, a special warm-up policy

is needed to ensure that the simulation can reach steady state conditions in a much shorter time. During the warm-up period, as long as the A&T facility has not received any lots of a particular wafer product, we allow the corresponding A&T product to be released immediately. After the first lot of the wafer product arrives at the warehouse, we continue to assume having sufficient stock until one month after the first arrival of the product. This policy also helps to avoid a large number of unfilled customer orders queuing in the LAE.

4 EXPERIMENTATION

In our study, we examine the on-time-delivery (OTD) performance of the A&T facility. OTD is defined as the percentage of completed lots that reach customers on or before the due dates. Due dates are randomly assigned to orders with a specific percentage of variation based on a mean value of 8 days. All experiments are performed with multiple replications (8 runs) using different random streams to determine the performance in each case with a certain level of confidence. The simulation runs are conducted for the model for periods of 6 years with a 3 year warm up.

4.1 Frequency of Inventory Update

Fig. 3 shows the OTD performance for different inventory information feedback and update intervals, ranging from 1 to 12 weeks. No general trend on the performance can be identified with increasing feedback and update interval from the graph. However, an investigation into the standard deviations of WIP and inventory of the wafer products indicates that there is an increasingly larger fluctuation of WIP and inventory with increasing update interval. This can be explained by considering the fact that lot cycle times in W/F is about 8 times that of A&T. Given Little's law, this also implies that WIP in W/F is approximately 8 times that of A&T's.

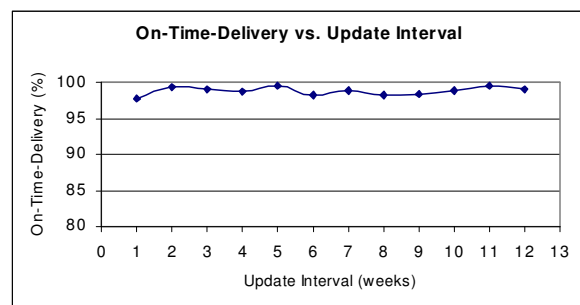


Fig. 3. Time-Delivery vs. Update Interval.

This WIP can thus act as a large buffer for the deviation between actual wafer lot release in W/F and the required wafers in A&T for the long update interval cases. Furthermore, at the beginning of simulation, the low initial inventory level in A&T causes more wafer lots to be released continuously, and this results in large WIP being built up for the long update interval cases. This large WIP will then be consumed dur-

ing the next inventory update when total WIP is found to be excessive, causing less wafer lots to be released. This “vicious” cycle of large fluctuation of WIP and inventory repeats itself.

4.2 Demand Variability

Fig. 4 shows the effect of increasing demand variation on the performance. From the results, it is obvious that increasing variation in demand deteriorates OTD. This can be explained by considering the impact of the order size variation on the inventory in A&T and subsequently WIP in W/F based on the wafer release formula.

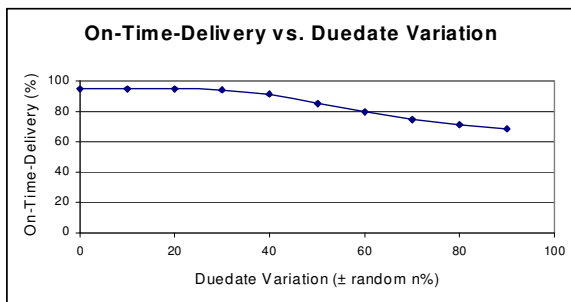


Fig. 4. On-Time-Delivery vs. Demand Variation.

4.3 Due-date Variability

Fig. 5 shows the effects of random variation of due dates on the performance. With the inventory threshold level fixed at a certain level, OTD decreases with increasing due date variations around a pre-defined due date of 8 days (from ±0 to ±90%). Increasing variation of due date at the early stage (i.e. from ±0 to ±30%) has negligible impact on the OTD performance. This implies that the supply chain model can accommodate due date variation up to 30%. Further variation of due dates requires higher inventory threshold levels to achieve good OTD performance.

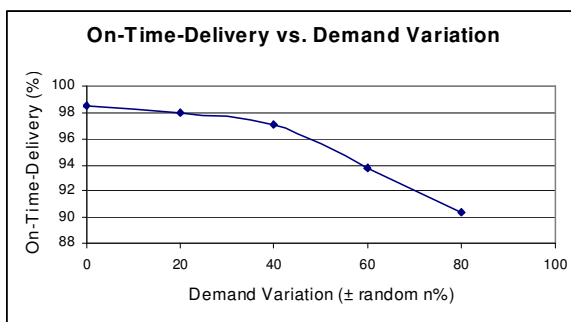


Fig. 5. On-Time-Delivery vs. Due date Variation.

4.4 Dispatching Priority for the last n Steps of Wafer Lots in W/F

A new dispatching rule has been introduced to rank the wafer lots for the last ‘n’ steps of product routings in W/F based on the demand and availability of that particular product in inventory. An Inventory threshold level I_T can be arbitrarily set for each wafer

product. For those wafer products with inventory levels greater than the thresholds, First-In-First-Out or Setup Avoidance rule is used as in the original model. However, if the inventory level falls below the threshold level, then that particular wafer product is given a higher priority in the backend (last ‘n’ steps) of the W/F. Further, lots that are closer to the end of their process flow are assigned higher priority than those at the beginning of the process flow if the lots share the same machine groups for processing. This ensures that the required wafer products reach AT as soon as possible.

A simulation experiment was performed by applying the dispatching rule at different stages in the W/F and setting the inventory level of W1 at a high level and that of W2 at a sufficient level. A demand spike (approximately 2 times the original demand) is introduced for a period of 9 weeks into one of the A&T products, which requires W2. Inventory threshold levels are set to 100 wafers for both wafer products (100 wafers were chosen based on earlier experiments with different inventory levels). The purpose of introducing the demand spike is to study the impact of a temporary demand change on the supply chain and to investigate the effectiveness of the new dispatching rule on the disruption. This scenario simulates a temporary demand change in the industry.

The simulation result is shown in Fig. 6. The dots on the graphs are the OTD performance for steady demand cases. When a demand spike is introduced, the system performance deteriorates (i.e. last 0 steps). However, when the new dispatching rule is applied in W/F (i.e. from last 20 steps onwards), OTD improves. The performance eventually reaches an optimum (i.e. OTD 1) as the rule is used in more and more processing steps of lots. This result can be explained by considering the impact of the dispatching rule on the two wafer products. The dispatching rule favors W2 over W1 initially due to excess inventory of W1, but when too many lots use the dispatching rule, the rule eventually alternates between W1 and W2. This occurs when inventory level of W1 drops to below a certain threshold and that of W2 reaches a certain threshold. To further verify our reasoning, we switched the dispatching rule trigger off for W1. The plot shows that OTD performance worsens after reaching an optimum (i.e. OTD 2).

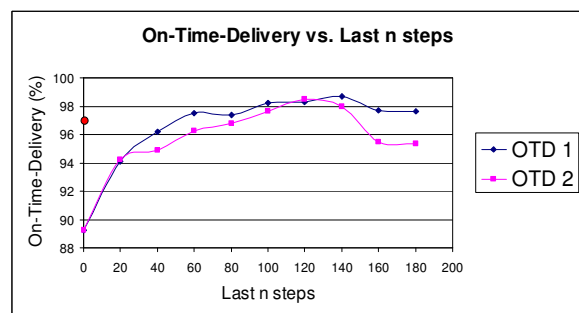


Fig. 6. On-Time-Delivery vs. Last n Steps.

5 CONCLUSION

This paper described the use of a detailed distributed simulation model for the analysis of a semiconductor supply chain. The study has provided quantified estimates of the performance. From our study, the following conclusions can be made:

- The impact of varying inventory update interval on OTD and tardiness performance is insignificant, although the effect on WIP and inventory (i.e. variance) is substantial.
- Increasing variations of demand and due date cause OTD performance to deteriorate. These variations play an important role in the performance of the supply chain [8].
- Assigning higher priority for wafer products that are 'short' in the warehouse of A&T can improve OTD performance. However, this method tends to cause other wafer products to be compromised.

The paper also demonstrates the usefulness of distributed simulation to evaluate the performance of supply chains. The use of an integrated model of information and material flows, as well as business and manufacturing processes enables capturing very detailed aspects of operations and interaction of individual entities in the supply chain. However, the results in this study are based on a hypothetical supply chain and therefore the results cannot be validated against the real system. To obtain the true characteristics of an actual system, it is recommended that supply chain simulations be validated against real supply chain performance.

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