Dynamic Inventory Model and Analysis for Semiconductor Silicon Wafer Material

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Keywords*: Silicon Cycles; Semiconductors; Supply and Demand; Boom and Burst; Supply Shortage*

ABSTRACT

Semiconductor silicon wafer material (SWM) is an essential substrate for semiconductor chip (SC), on which electric circuit patterns are fabricated in the manufacturing process. While the stable SWM supply is a critical management issue for semiconductor industry, the instability in the supply and demand balance has frequently disturbed the smooth production planning and procurement operation. The timely and adequate dynamic analysis for the industry inventory which reflects the supply and demand balance is still the key issue for semiconductor industry. In this research, we developed the specific system dynamics (SD) model aiming to evaluate the SWM inventory in semiconductor industry for the first time. The optimized SD model as the result made it possible to simulate the dynamic inventory behaviors successfully using the available reference data and the simulation revealed the dynamic inventory cycles in the SC industry whose cycle period is approximately 22 months. At the same time, it indicated that the inventory has been declining significantly in the past two years, which is consistent with a prevailed concern for the supply shortage during the period. With these results, we verified enough potential of the developed model frame work to lead valuable insights for the determinations of actual business policy and strategy when used with the industry scenarios.

1. INTRODUCTION

1.1. SWM Market

SWM is the precisely machined and polished wafer substrate made from highly purified silicon ingots. The quality and technology are critical to decide the leading edge SC performance, which has been discussed by the experts (O'Mara et al., 1991).

A unique market characteristic of SWM market is that the wafer size has been periodically shifted to the larger diameters synchronizing with the evolving SC production technology. To materialize "Moore's law" (Moore, 1965) in the economic scale of SC manufacturing, semiconductor industry has enlarged the wafer diameter periodically to increase the number of chips per wafer efficiently.

Actually, the wafer size has been continuously enlarged from below 100mm through 125mm, 150mm and 200mm to 300mm for today. While the blue print of size enlargement in SC manufacturing process has been drafted in detail by the industry organization such as Semiconductor Equipment and Materials International (SEMI), the actual timing of transition in the wafer market has not been fully controlled. It has depended greatly on the market environments such as the maturity of new technology, the industry's financial conditions, the global economy and others. For more details, the empirical study for the wafer size transition dynamics indicates that the dominance duration of each wafer size in the market is estimated as 8 to 10 years and the accumulated wafer demand of each generation wafer in size is following to the logistic growth model (Ogawa, 2013).

1.2. Dynamics for Supply and Demand Imbalance of SWM Market

As the SMW is not replaceable for SC manufacturing, the stable supply is a critical issue for SC industry. However, the industry has frequently experienced concerns for the supply shortage which jeopardized the planned SC production and ramp-up of the new production facilities in history.

As the latest case, the boomed investment for semiconductor production facilities reached the highest during 2017-2018 driven by large-scale facility investments by memory vendors such as Samsung and SK Hynix in Korea and China's massive government investments to beef up SC production internally due to the Made in China Plan in 2025 (Johnson, 2018). As a result, the SC industry struggled to secure more silicon wafers during 2016-2018 to meet market demand for their SC production (ShinEtsu MicroSi, 2017). On the other hand, SWM industry was hesitant to invest in the new production capacity without confirming enough price rise of their wafer products to satisfy with the return on investment (ROI). Such market situations generated a global supply shortage concern of SWM for the past few years.

In the SWM market, the supply and demand imbalance tends to be induced during the transition to the next wafer size in the market (Ogawa, 2013). This is because several inevitable time delays in the production and supply chain process are expected to cause a supply mismatch prominently over the demand surge driven by the ramp-up of new SC manufacturing factories. The essence of this dynamics is expected to be common with other manufacturing industry (Sterman, 2000)

Except the common dynamics in manufacturing industries, the following unique market factors are also expected to influence on the supply and demand imbalance of the SWM (Ogawa, 2010).

Internal competitions within the industries
The fierce competition in SC industry makes the companies overinvest to the new products aiming at the same new market, which leads the inflation of wafer demand in short period. Also during the transitions to the larger size wafers, the SWM companies have to compete to start up the new production facilities to gain a dominant position of the new market, which causes the over shipment to the SMW market triggering the market imbalance.

Changes in the production yield
In an initial stage of new semiconductor products, the production yield is still immature and more wafer substrates must be infused into the production lines in order to compensate the production loss over the planned production quantity. However, as the production yield gets matured with the learning curve (Gruber, 1992), the SC companies need to reduce the quantity of wafer input sharply, which leads a decline of wafer demand during a short period. Similarly, the SWM companies struggle to respond to the increasing initial market order for the new large size wafers because of their immature production yield, however they see an overcapacity soon as the yield gets improved significantly by the learning curve.

Procurement strategy of SC companies
SC companies strategically order the wafers responding to the market conditions. Especially, when the supply and demand balance of the SWM is tilting to the supply tightness, they are forced to order the extra quantities to avoid a risk of the shortage for their future production. Such essential behaviors will lead the inflation of wafer demand and the phantom orders, which alleviates the imbalance of wafer market.

Investment strategy of SWM companies
On the other hand, SWM companies also respond to the market demand strategically to extract the better wafer price and profit through the negotiation with SC companies. In these days, they are very prudent to invest the new capacity even if a concern for the supply shortage is well-recognized. The SWM companies have to decide the future investment plan with a confirmation of positive price environments and need to ramp up the new capacity gradually to maintain the positive market condition for them. This attitude is expected to impact on the supply and demand balance.

1.3. Purpose of Research

While the stable wafer supply is a critical management issue for semiconductor industry, the imbalance of supply and demand has frequently emerged in history. Although SC and SWM industries have estimated the demand and supply balance from time to time, the industries have not established the adequate process to evaluate the material inventory with the dynamic changes which are susceptible to a variety of market conditions.

Our final goal of whole research project is to suggest the adequate industry policies and scenarios for their operation and investment strategies with using the system dynamics simulations, which will bring a mutual benefit both for SC and SWM industry by avoiding the unnecessary imbalance of SWM market. However, as the first step toward the final goal, we need to create the SD model frame work which is able to incorporate with the several alternative scenarios for the key variables.

With the backdrop, this research aims to achieve the multiple purposes. Those are to construct the SD model frame work which is able to reproduce the observed market trends reasonably as the reference modes and to verify the SMW market dynamics and extract the optimum values for key parameters by simulations, and the final one is to reveal the dynamic changes of SWM inventory in SC industry and understand the basic behavior and characteristic.

2. THE DYNAMIC INVENTORY MODEL

2.1. Model Structure

The purpose of modeling for this research is not emphasized on the precise description of market structure which requires a fully combined model between SC and SWM industry. Our simplified model to simulate the observed market trends consists of three sectors, namely, Wafer Inventory in SC industry, Wafer Order and Wafer Manufacturing and Shipment. Figure 1 indicates the causal structures and key variables in each sector. The model contains a variety of causal loops. For an example, there are the eighteen causal loops linked with Industry wafer inventory (IWI), in which nine reinforcing and balancing feedback loops are interrelated respectively.

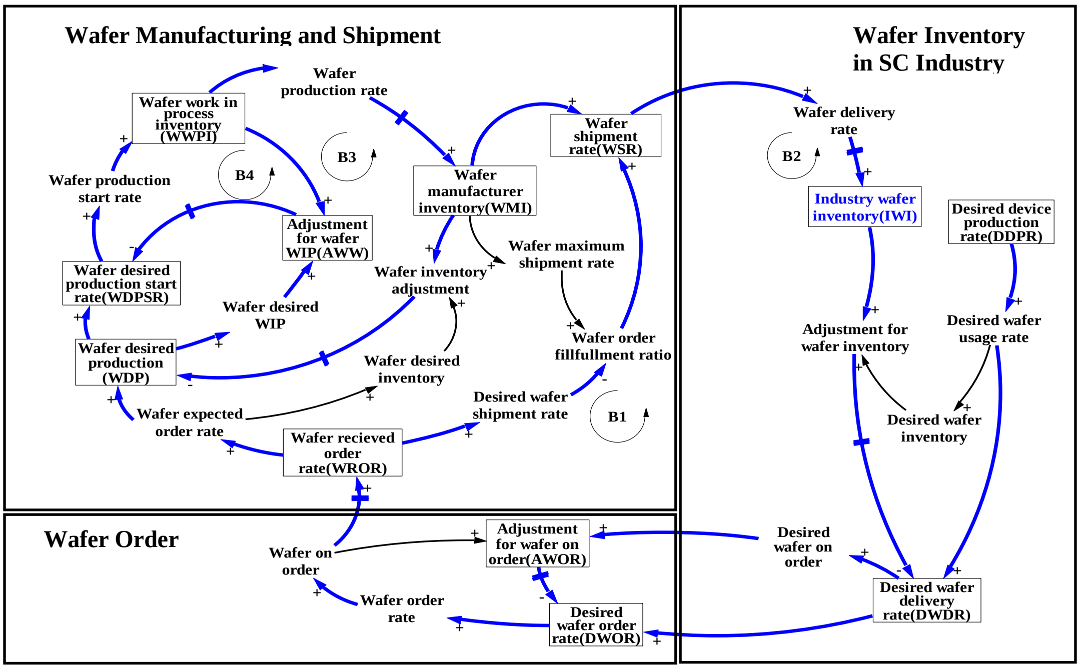

Figure 1 Causal Structure of the Dynamic Inventory Model

The main related loops to dynamics of IWI, which is our interest to observe, are traced by the causal-connections in blue color. Initially, the desired device production rate (DDPR) given as an exogenous variable drives Desired wafer delivery rate (DWDR), which increases Wafer received order rate (WROR). Consequently, this initial wafer demand leads the increment of Wafer shipment rate (WSR) and IWI through the causal flows. Subsequently, two major balancing feedback loops are expected to work for the increment of IWI. B1 represents the direct balancing effect to IWI. The increment of IWI will reduce WROR through DWDR, Adjustment for wafer on order (AWOR) and DWOR, which will sustain WSR and reduce IWI. On the other hand, B2 indicates the indirect balancing effect to IWI. We can see the outer large loop which is formed through Wafer desired production (WDP), Wafer desired production start rate (WDPSR) and Wafer work-in process inventory (WWPI) after a sequence of DWDR, DWOR and WROR. This loop will also sustain WSR and reduce IWI by adjusting the wafer manufacturing and shipment.

Further, the local balancing loops B3 and B4 react to the changes of IWI through B2. These are related to the inventory adjustment in SMW industry. B3 will cause a balancing effect for WDP through WWPI and Wafer manufacturer inventory (WMI). Also B4 will work for WDSPR through WWPI and Adjustment for wafer WIP (AWW). These local balancing loops will convert the balancing effect of B1 into reinforcing effect for IWI.

The following sections will explain the detail structure and function of each model sector

2.2. Functions for Model Sectors

Figure 2-1, 2-2 and 2-3 show the model details for Wafer Inventory in SC industry, Wafer Order and Wafer Manufacturing and Shipment respectively.

Wafer Inventory in SC industry

The sector describes the wafer inventory dynamics in SC industry, where the stock and flow structure from the wafer delivery to wafer usage rate is included. The desired wafer usage rate, which is driven by the desired device production rate, is given as an exogenous variable. The industry wafer inventory is expressed as a stock balance between the wafer delivery and usage. Also, the desired wafer delivery is decided by the desired usage and inventory adjustment.

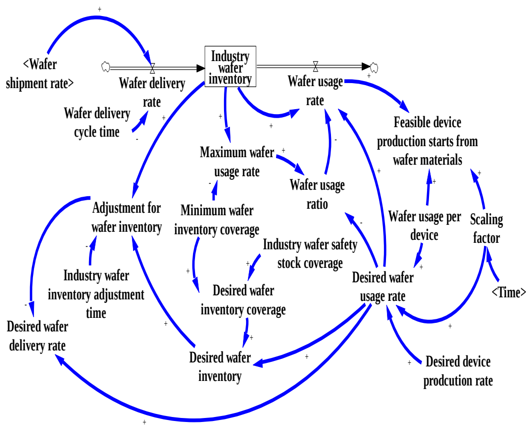

Figure 2-1 Model for Wafer Inventory in SC Industry

Wafer Order

Wafer order in SC industry is expressed as a stock balance between the wafer order and arrival rate. The wafer order rate is linked to the desired wafer delivery rate in Wafer Inventory in SC industry and the adjustment for wafer on order, which is decided by the desired wafer on order.

Wafer Manufacturing and Shipment

The sector is indicating the wafer manufacturing and shipment process in SWM industry, whose model structure is quite common to the typical manufacturing industry model (Sterman, 2000). The basic frame work is expressed by the stocks and flows from wafer order in to wafer shipment rate as shown in Figure 2-3. The sector inventory consists of the wafer work in process inventory and wafer manufacturer inventory. These are respectively adjusted by their desired inventory level which is associated with the wafer expected order rate. Further, the wafer production start rate is decided by the industry wafer capacity and desired production rate interrelated with the wafer production fulfillment ratio. Finally, the wafer shipment is streamed with a control by the wafer order fulfillment ratio. This dynamics is also common to the conventional manufacturing industry model.

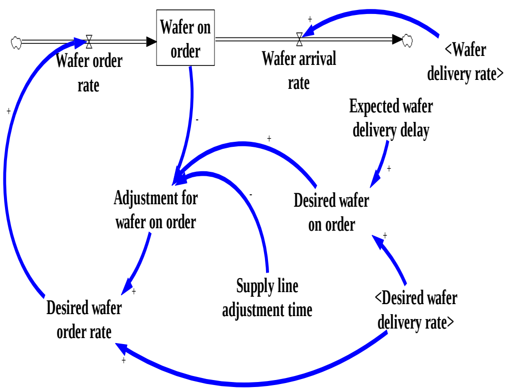

Figure 2-2 Model for Wafer Order

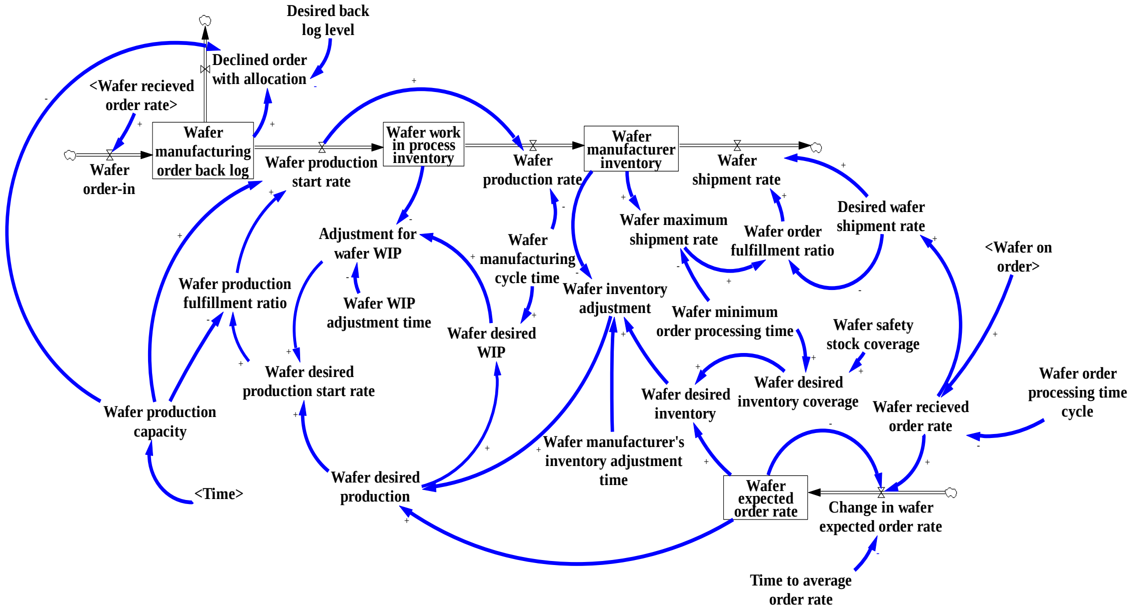

Figure 2-3 Model for Wafer Manufacturing and Shipment

3. MODEL SIMULATIONS

3.1. Basic Simulations

Before applying the SD model for the actual wafer market, we investigated the basic behaviors of key variables with using the equilibrium model. In our model, the unit of wafer quantity is described by the surface areas, namely, million square inches (MSI) and the semiconductor device production demand, whose variable is the desired device production rate, is measured by million unit/month.

As an example of basic simulations with the equilibrium model, Figure 3-1 demonstrates the dynamic responses of the industry wafer inventory over the step change of the desired device production rate shown as Figure 3-2.

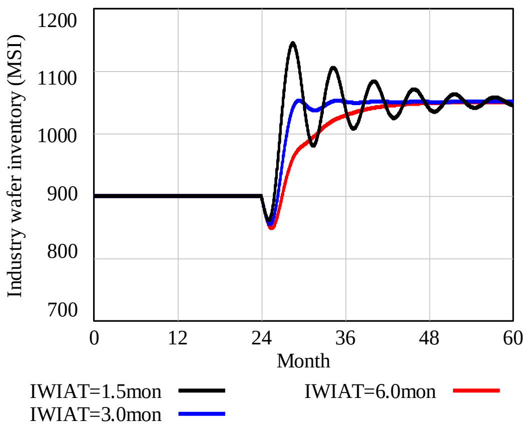

Figure 3-1 Simulation for Behaviors of Industry Wafer Inventory from the Equilibrium State

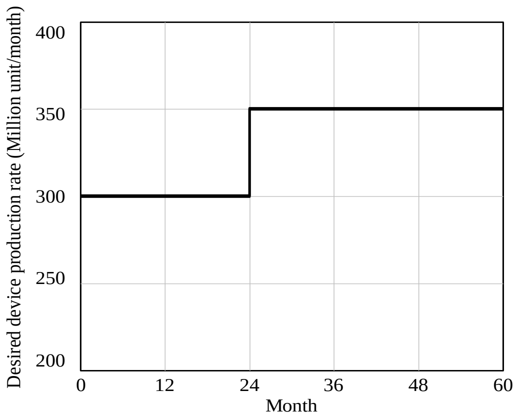

Figure 3-2 Semiconductor Production Unit Demand for Basic Simulation

In this simulation, the device production rate is initially fixed at 300 million unit/month as the equilibrium state (at t=0) and raised to 350 million unit/month at 24 month (at t=24). We can observe that the industry wafer inventory is shifting to the new level of inventory with some time delay after a step increase of the device unit demand. In the details, the inventory is oscillating to the new equilibrium depending on the industry wafer inventory adjusting time (IWIAT). As shown in Figure 3-1, we can recognize that the inventory transition is getting smoother reasonably as IWIAT becomes longer, which reduces the over and under shoot effects from the equilibrium level.

As same as this example, we confirmed that our model can lead the reasonably behaviors in other key variables responding to a variety of simulation conditions including some ultimate cases.

3.2. Reference Data

For the actual market simulations with above SD model, we incorporated the available market data into the model to describe the reference modes and optimize the variable parameters. The details of the reference data are as follows.

Wafer Shipment, Production and Inventory in SWM industry

The monthly data for the wafer shipment, production and inventory for the Japan-based factories in SWM industry are available from the Japanese government- Ministry Economy, Trade and Industry (METI, 2019). Similarly for the global wafer shipment, SEMI has reported the quarterly wafer shipment (SEMI, 2019). By comparing the wafer shipment data as the quarterly base between METI and SEMI, we evaluated that the shipment by the Japan-based factories has occupied 50 to 60% of the global wafer shipment in history. Therefore, we introduced the scaling factor as the table variable in the SD model to convert the monthly data from METI to the global data as the reference modes.

Wafer Production Capacity in SWM industry

The historical global wafer production capacity in SWM industry has been investigated and provided by an industry research firm (Gartner, 2017). Also the major SWM company has reported their view for the industry capacity in the financial reporting from time to time (SUMCO, 2019). We summarized these available data for the wafer production capacity which is incorporated in the SD model

Semiconductor Device Unit and Wafer Demand

In the SD model, the semiconductor device unit demand and wafer demand are given as the exogenous variables, which are named as the desired device production rate and desired wafer usage rate respectively. The global semiconductor device unit shipment has been reported monthly by Worldwide Semiconductor Trade Statistics (WSTS,

2018) and we used the historical data to estimate the wafer demand in our model. Actually we have recognized the fairly good correlation between the semiconductor device unit and wafer shipment. Figure 3-3 shows the linear relation between them for the past twenty years. With the empirical analysis, we are evaluating the global wafer demand in the model with the linear relation.

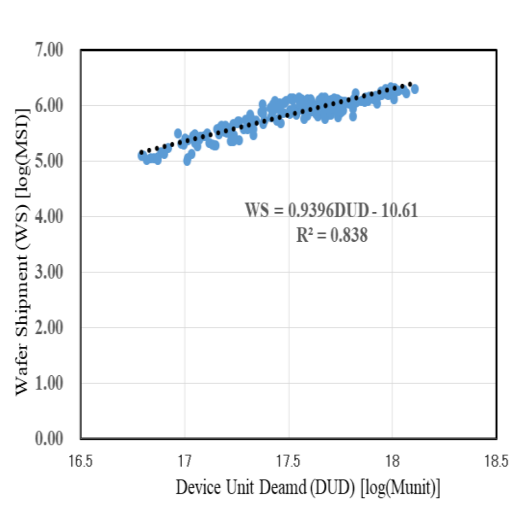

Figure 3-3 Relation between Device Unit Demand and Wafer Shipment

3.3. Model Parameters

The SD model includes the market parameters to be decided by considerations from the industry perspectives and any secondary research. Each model sector includes the following industrial parameters.

Wafer Order

Expected wafer delivery delay (EWDD): The expected time for the ordered wafers to be shipped to the SC companies

Supply line adjustment time (SLAT): The required time to adjust wafer on order to the desired level after the recognition of wafer delivery

Wafer Inventory in SC industry

Industry wafer safety stock coverage (IWASC): The safety stock level of wafers that the SC companies desire to retain for their productions

Minimum wafer inventory coverage (MWIC): The minimum stock level of wafers to sustain the productions in SC industry

Industry wafer inventory adjustment time (IWIAJ): The required time to adjust the wafer inventory to the desired level

Wafer delivery cycle time (WDCT): The required time to accept and recognize the wafer delivery by SC companies

Wafer Manufacturing and Shipment

Wafer order processing time cycle (WOPTC): The process time for the wafer order from the SC companies to be recognized by SWM companies

Time to average order rate (TAOR): The average duration to estimate and recognize the changed wafer order

Wafer safety stock coverage (WSSC): The stock level of wafers that the SWM companies desire to reserve to sustain their productions

Wafer minimum order processing time (WMOPT): The required minimum time to ship the wafers from the stocked inventory in SWM companies

Wafer manufacturer's inventory adjustment time (WMIAT): The required time to adjust the inventory to the desired level by SWM companies

Wafer manufacturing cycle time (WMCT): The averaged cycle time to manufacture the products as the final wafer products

Wafer WIP adjustment time (WWAT): The required time for SWM companies to adjust their WIP product inventory to their desired level

Desired back log level (DBLL): The desired order back log level for SWM companies which is a criteria to decide if the new order is declined or not.

3.4. Market Simulations

We performed the simulations for SWM markets with an incorporation of the reference market data into our SD model. For decisions of model parameters explained in the previous sections, we contemplated the information from the industry experts and interviews with the key SWM companies for the determinations. The table 1 shows the decided values for model parameters used in the market simulations by our SD model.

The duration for the simulations is from January 2000 to December 2018 and all the simulation unit is a month. The desired wafer usage rate, which indicates the wafer demand for semiconductor desired production, is given as the exogenous data for all simulations as shown in Figure 3-4. In the figure, one extraordinary drop is outstanding in 2009. We have confirmed that the sharp slump was driven by the economic shock known as "Lehman Shock", not by any special internal market cause.

Base Case

Figure 3-5, 3-6 and 3-7 show the simulated results of the wafer shipment rate, wafer manufacturer inventory and wafer production rate respectively as Base Case whose parameters are in Table 1. In these figures, the actual market references, which were explained in section 2.2, are added for the comparisons. Overall, the Base Case in Figure 3-5 and 3-7 is capturing the general trends of the market references well. However, we can recognize a large gap between the simulation and reference for the wafer manufacturer inventory in Figure 3-6.

Table 1 Model Parameters (month)

Parameter	Base Case	Optimized Case
Wafer Order		
EWDD*	2.00	0.30
SLAT	2.00	2.00
Wafer Inventory in SC industry		
IWASC	3.00	3.00
MWIC	1.00	1.00
IWIAJ*	8.00	4.00
WDCT	1.00	1.00
Wafer Manufacturing and Shipment		
WOPTC	1.00	1.00
TAOR	3.00	3.00
WSSC	1.00	1.00
WMOPT*	1.00	0.69
WMIAT*	3.00	4.96
WMCT	3.00	3.00
WWAT*	3.00	2.08
DBLL	3.00	3.00

Note: Parameters with an asterisk mark were only optimized

Optimized Case

Aiming at resolving the large gap in Figure 3-6, we applied the optimization function in SD simulation software- Vensim (VENTANA systems, 2019). However, for the parameters which have the high credibility from the industry information, we kept the same value as Base Case and applied the optimization process only for the parameters with high uncertainty. Actually, we applied the optimization process only for EWDD, IWIAJ, WMOPT, WMIAT and WWAT.

By the minimization of payoff function with the market references by Powell method, the model parameters were decided as Optimized Case in Table 1. The Optimized case in Figure 3-6 demonstrates the better fitness than the Base Case with the actual references. On the other hand, a spiky increase due to Lehman Shock is observed in Figure 3-6 while not seen in the actual reference. At present, we are considering that the difference comes from a bias that the actual reference has been estimated based on the Japan-based factories in SWM industry while the simulation relies on the global device unit production demand.

The major differences in model parameters between Base and Optimized case are on IWIAJ (Industry wafer inventory adjustment time) and WMIAT (Wafer manufacturer's inventory adjustment time), which implies that the effects from balancing loops B1, B2, and B3 in Figure 1 are expected to be adjusted by the optimization. WMIAT in Optimized case was adjusted from 3.00 to 4.96 month. It tells us that the wafer industry as whole is slower to react to the required inventory adjustment. As a consideration for the reason, the drastic adjustment of inventory is expected to be more prudent than our consensus because it will impact the short-term market demand influencing on financial performance of wafer manufacturers. On the other hand, the shorter IWIAJ in Optimized case indicates a faster inventory adjustment for SC industry than our expectation. We consider that the superior market position against the wafer industry makes it possible in general (Ogawa, 2010).

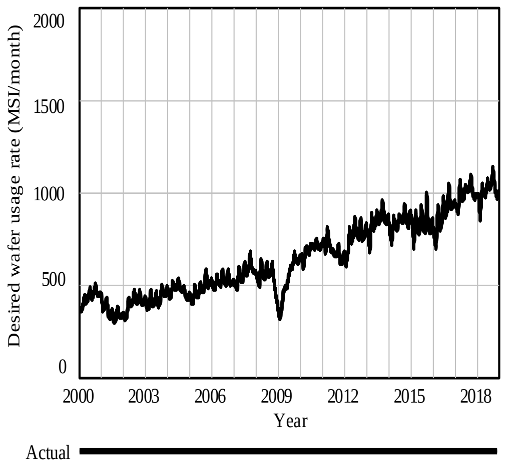

Figure 3-4 Semiconductor Wafer Demand

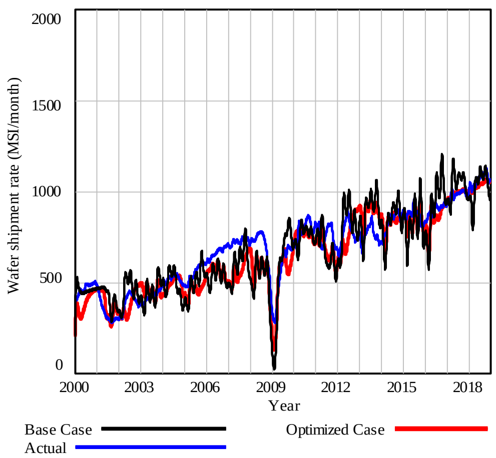

Figure 3-5 Simulation of Wafer Shipment Rate

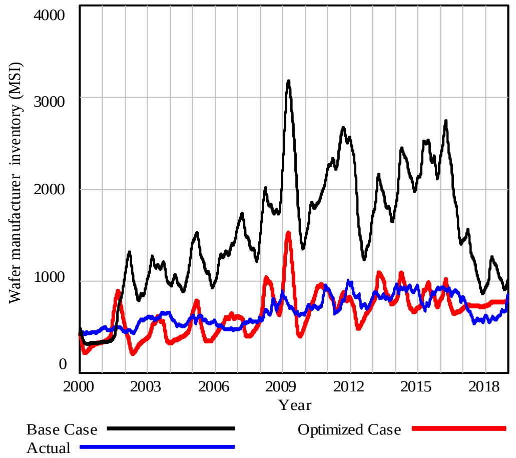

Figure 3-6 Simulation of Wafer Manufacturer Inventory

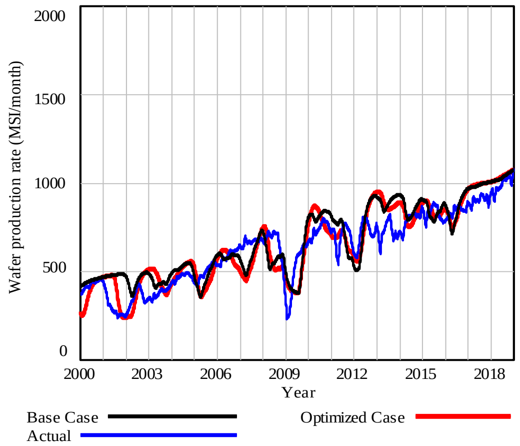

Figure 3-7 Simulation of Wafer Production Rate

4. CONSIDERSTIONS FOR WAFER INVENTORY IN SC INDUSTRY

As a key result of this research, our simulation successfully revealed the dynamic changes of wafer inventory in SC industry for the first time. Figure 4-1 shows the behavior of inventory as MSI and Figure 4-2 indicates the inventory level which is a ratio between the wafer inventory and wafer usage.

We can verify that Figure 4-1 represents that the trend of inventory has reasonably increased in line with the wafer demand as Figure 3-4. Further, we can observe the cyclical behaviors clearly in Figure 4-1 and 4-2. At present we conclude that the cycle is reflecting the essential characteristic cycle time of the SC industry to adjust the inventory to the desired level while an unexpected impulse by Lehman Shock in Figure 4-2 is recognized again in 2009.

In general, the inventory cycle has been known as "Kitchin cycles" (Kitchin, 1923) reporting that the minor economic cycle duration is about 40 months. For the wafer inventory cycles, our first observation in this simulation identified that the cycle duration was about 22 months as the average by 2009 and it has become longer and unclear after 2013. We need to perform further analysis to understand the verified reasons for the duration change. However, our initial insight implies that it is due to a market turbulence and the cautious attitude of SC companies to reserve the wafer inventory during a few years after the great east Japan earthquake and the Thailand flood in 2011. As matter of fact, the both natural disasters, the unprecedented earthquake in particular, destroyed the supply chain of electronics materials significantly including the SWM. As a result, a serious supply shortage happened during 2012-2013 (Ogawa, 2011; Kate, 2011). We consider that this critical experience has made the SC companies more aggressive to reserve the wafer inventory during a certain period as their business continuity planning (BCP).

As described in section 1.2, the SC industry struggled to secure more silicon wafers during 2016-2018 which was triggered by the boom of investment for the new generation devices. In Figure 4-1, the simulated wafer inventory by our model shows a big dent after 2016, which can be explained by above market situation well.

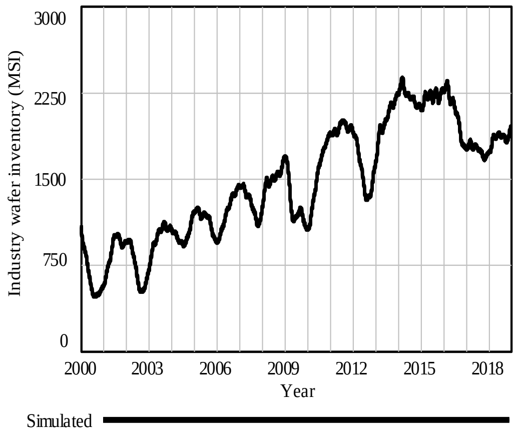

Figure 4-1 Simulation of Wafer Inventory in SC Industry

Consequently, the inventory drop is causing a wide adjustment of inventory level to 1.8 month in the mid of 2018 as shown in Figure 4-2. This consistency is demonstrating a validity of our model performance.

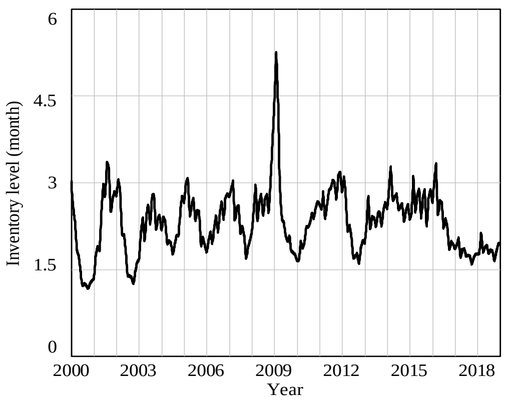

Figure 4-2 Simulation of Wafer Inventory Cycles in SC Industry

5. CONCLUSIONS

In this research, we developed the specific SD model to simulate the SWM market and evaluate the wafer inventory in SC industry for the first time. We verified that the optimized model was able to reproduce the consistent market trends with the actual reference data, which demonstrated the enough ability to lead valuable insights to consider the actual business policies when applied for the specific scenarios in the future research.

Also, we recognized that wafer inventory in SC industry had the unique cycles for the first time. The cycle duration was estimated to 22 months as average which is shorter than economic inventory cycles (Kitchin, 1923). While the cycle pattern is expected to be decisive by the endogenous characters of SWM market, the influences by market turbulences such as the impacts of financial crisis and natural disasters are expected to have interfered the patterns after 2009. Finally, the optimization of parameters suggested that the response of wafer industry to the required inventory adjustment should be slower than our expectation whose adjustment time was estimated as 5.0 months approximately, which is expected to be related to a prudent attitude of wafer manufacturers to change financial performance of wafer manufactures in short-term drastically.

In our subsequent research we plan to suggest the adequate industry policies both for SC and SWM industry to avoid the unnecessary imbalance of SWM market by the model simulations which include the practical scenarios for the influential factors explained in section 1.2.

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