Decision Framework for Capacity Expansion in Semiconductor Manufacturing: Assessment of Micron Singapore

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Project Title: **Decision Framework for Capacity Expansion in Semiconductor Manufacturing: Assessment of Micron Singapore**

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I. Introduction

Investment in capacity expansion to meet the increasing demand in the Semiconductor industry is one of the most critical decisions for a manufacturing organisation with production facilities (N.Juka et al, 2007). Capacity decision to increase wafer output can vary in form: building a new fabrication plant (fab)[1] in a new location or expanding the current fab. Capacity expansion is a very subtle problem and not as simple as just carrying out analyses based on a few factors (Porter, 1980).

II. Fab Expansion versus Fab Construction: Factors Analysis

(Please refer to the Appendix to see supporting documents for each section accordingly.)

1. Assumptions & Conditions:

Assumptions:

i. Utilisation (%) and Availability (%) always stay constant over time.

ii. Every machine has already been working for a period of time.

iii. Waiting time is negligible.

iv. There is an unlimited number of FOUPs available.

Justification:

For (i), since the rate of deterioration of the machines is not given except Utilisation (%) and Availability (%), and taken the fact that companies need to constantly maintain the equipment so that the productivity is not affected as the machines age, we assume that companies are able to ensure the performance of machines. Hence, Utilisation and Availability are constant. For (ii) and (iii), every machine has already been working for a period of time and the waiting time is negligible in order to simplify our calculation and modelisation in this scenario.For (iv), since the number of FOUPs available is not mentioned, and the number of FOUPs, acting as the transition of wafers between stages, should be enough to service our production depending on target wafer output, we assume that there is an unlimited number of FOUPs available so that our calculations are not interfered yet the assumption is still properly justified.

2. Capacity of Machine at Each Step

Stage 1: We need to calculate the amount of time that the machine is utilized each week by the equation: $time\ of\ machine\ usage\ per\ week = 7 \times 24 \times 60 \times Utilisation\%$

[1] Hereafter, the wafer fabrication plant will be named as fab for short.

Stage 2: Since in every RPT value (mins), the machine can produce a batch of wafers, the number of batches of wafers produced in a week is:

$$\left\lfloor \frac{7 \times 24 \times 60 \times Utilisation\%}{RPT} \right\rfloor$$

Stage 3: We calculate the number of wafers that go through each step by the equation:

$$no. of\ wafers\ =\ load\ size\ x\ chamber\ count$$

Stage 4: We calculate the weekly the number of wafers that go through one step (or the capacity of each step of machine) by the equation :

$$no\ of\ wafer\ from\ each\ step\ =\ load\ size\ \times\ chamber\ count\ \times\ \left\lfloor \frac{7\ \times\ 24\ \times\ 60\ \times\ Utilisation\%}{RPT} \right\rfloor$$

3. Number of Machines & Capital Investment required

3.1 Number of Machines

In order for the fab output to be 5000 wafers per week, the output of each Workstation in each step is 5000.

Let the ***Raw Processing Time*** be ***RPT***.

Let the ***capacity per week of the WS in a specific step*** be ***a***.

Let the ***number of wafers*** that can be produced in 1 batch be ***b***.

Let the ***number of extra machines*** required for each step be ***n***.

Let the ***extra minutes of utilisation*** of the work station after finishing 5000 outputs for 1 step be ***c***.

The ***subtext*** symbolizes ***the order of a step*** in the workstation. For example, a_i symbolizes the capacity per week of the WS of the first step among the same type of machines.

a. RPT basis = 1

Stage 1a: We sort the data by name in order to find the steps that one WS must process. Then we sort these steps in descending order of capacity per week.

Stage 2a: Starting with the first step, we determine the number of machines needed for the first step by:

$$n = \left\lceil \frac{5000}{a} \right\rceil$$

Stage 3a: We calculate the amount of time that the workstation can still be used after finishing 5000 outputs for the first step by the equation:

$$c_1(mins)\ = \left\lfloor \frac{a_1 n_1 - 5000}{b_1} \right\rfloor \times\ RPT_1$$

Stage 4a: Based on the number of minutes left for that workstation, we calculate the number of outputs for the next step that can be produced with that amount of time by the equation:

$$c_x = \lfloor \frac{\lfloor \frac{c_{x-1}}{RPT_x} \rfloor \times b_x + a_x n_x - 5000}{b_x} \rfloor \times RPT_x$$

Stage 5a: Repeat stage 4 until the last step.

Stage 6a: Find n_x for the last step in the workstation so that:

$$\lfloor \frac{c_{x-1}}{RPT_x} \rfloor \times b_x + a_x n_x - 5000 > 0$$

Stage 7a: Add up the number of machines needed in each step in order to find the total number of machines needed for each workstation.

$$total\ no.of\ machines = \sum_{i=1}^{x} n_x$$

b. RPT basis > 1

Stage 1b: We sort the data by name in order to find the steps that one WS must process. Then we sort these steps in descending order of RPT.

Stage 2b: Starting with the first step, we determine the number of machines needed for the first step by:

$$n = \lceil \frac{5000}{a} \rceil$$

Stage 3b: We calculate the number of wafers that can be produced together with the last batch of the previous step because of the RPT basis > 1 which allows two steps to be carried at the same machine. We symbolize this number as *r*, and calculate it in this equation:

$$r_x = (\lfloor \frac{c_{x-1}}{RPT_x} \rfloor \times b_x + a_x n_x - (5000 - r_{x-1}))\%\, b_x$$

- 5 % 2 means that the remainder after 5 when divided by 2, which is 1
- Since 1 chamber cannot carry out 2 steps at the same time,

  $$r \leq load\ size \times multiple\ of\ chamber$$
- If $r < load\ size \times lowest\ number\ chamber\ count$, then:

  $r = load\ size \times (chamber\ count - 1)$
- Else:

  $$r = load\ size \times a\ number\ of\ chamber\ count\ that\ is\ smaller\ than\ chamber\ count$$

Stage 4b: Based on the number of minutes left for that work station, we calculate the number of outputs for the next step that can be produced with that amount of time by the equation:

$$\left\lfloor \frac{\lfloor \frac{c_{x-1}}{RPT_x} \rfloor \times b_x + a_x n_x - (5000 - r_{x-1})}{b_x} \right\rfloor \times RPT_x = c_x$$

<u>Stage 5b</u>: Repeat step 3-4 until the last step.

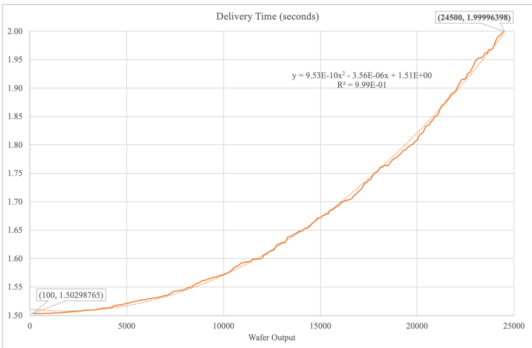
<u>Stage 6b</u>: Add up the number of machines needed in each step in order to find the total number of machines needed for each workstation.

$$total\ no.of\ machines = \sum_{i=1}^{x} n_x$$

3.2 Capital Investment required

In order to find the Capital Investment required for machines to produce a capacity of 5000 semiconductors per week, we multiply the number of machines in each workstation found in 3.1 with the respective tool price from the datasheet given.

4. Wafer Output & Delivery Time

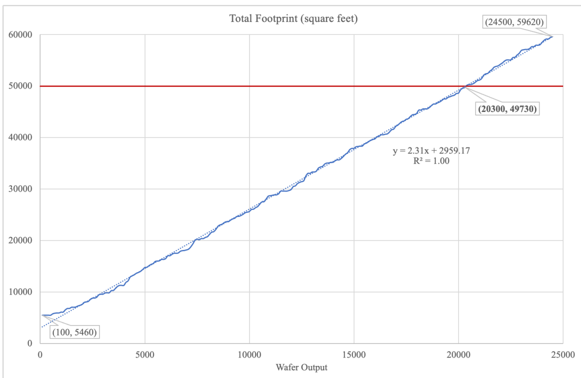


From part 4 onwards, the calculation of data is based on the wafer output being in multiples of 100.

The relationship between wafer output and delivery time is represented by a quadratic curve. We must take note that the maximum wafer output a location can produce before the delivery time exceeds 2 minutes is 24,500 wafers per week.

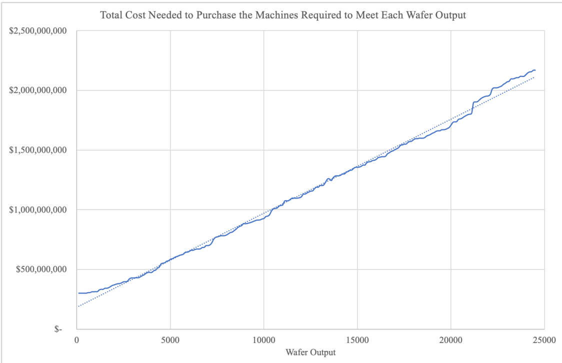
5. Wafer Output & Footprint Requirement

From the calculation of data, the wafer output is linearly related to the footprint requirement. We must take note that the maximum wafer output a building can produce before the footprint exceeds 50,000 sq.ft. is 20,300 wafers per week.



6. Wafer Output & Total Capital Investment Required

From our data from part 4 and 5, we know that the maximum number of buildings that can be built on a particular location is 2 buildings for which both buildings cannot host the maximum number of machines per building at the same time; otherwise, the delivery time of the location will exceed 2 minutes.



We also have to use up the space in the existing buildings to the maximum limit first before we consider constructing a new building as, from the graph here, we know that the relationship between wafer output and total cost of machines is linear. Since any two or more points on the graph which has a combined number of machines of x will always have a higher cost than a single point which has x number of machines due to the nature of a linear graph, it is not rational to not use up the building space to its maximum limit.

As we increase the wafer output from 5,000, the number of locations and the number of buildings in each location will vary. Only one of either scenario will we encounter in the case that the delivery time and/or footprint has been maximized.

<u>First scenario</u>: all locations have only one building in each location. Each building has already maximized its footprint. A breakdown comparison of the cost can be shown for a wafer output of $20{,}400 = (20{,}300 \times 1 + 100)$

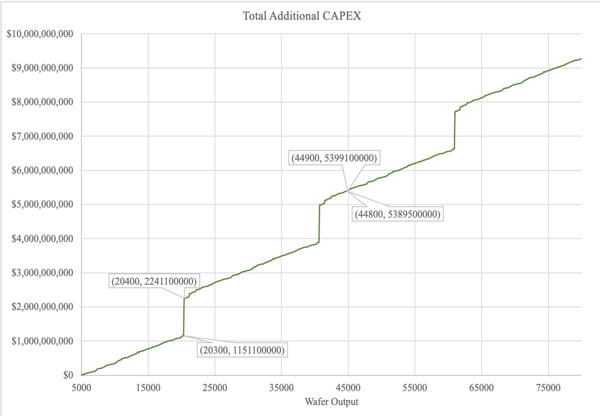
Options	**Expand in original location by constructing a 2nd building**	**Build in a new location by constructing a 1st building**
Cost of additional machines in owned location	$1,757,300,000 (461 machines needed)	$1,737,300,000 (459 machines needed)
Cost of additional machines in new location	$0 (0 machines needed)	$301,600,000 (53 machines needed)
Cost of additional construction	$1,070,000,000	$1,000,000,000
Deducting the cost to acquire machines that are already owned to	- $586,200,000	- $586,200,000

produced a wafer output of 5,000		
Total	**$2,241,100,000**	**$2,452,700,000**

Therefore, from this table, it is cheaper to expand in the original location. This scenario will be repeated every $20300n + 100$, where n is a positive integer.

Second scenario: all locations except for the original location have one building while the original location has 2 buildings (inclusive of the existing building). One of the buildings has already maximized delivery time. A breakdown comparison of the cost can be shown for a wafer output of $44{,}800 = (20{,}300 \times 2 + 4200)$

Options	**Expand in 2nd location by constructing a 2nd building**	**Build in a new location by constructing a 1st building**
Cost of additional machines in original location	$5,389,500,000 (549 machines)	$1,737,300,000 (456 machines)
Cost of additional machines in bought location	$1,757,300,000 (461 machines)	$1,737,300,000 (456 machines)
Cost of additional machines in new location	$0 (0 machines needed)	$510,700,000 (119 machines)
Cost of additional construction	$2,140,000,000	$2,000,000,000
Deducting the cost to acquire machines that are already owned to produced a wafer output of 5,000	- $586,200,000	- $586,200,000
Total	**$8,700,600,000**	**$5,399,100,000**

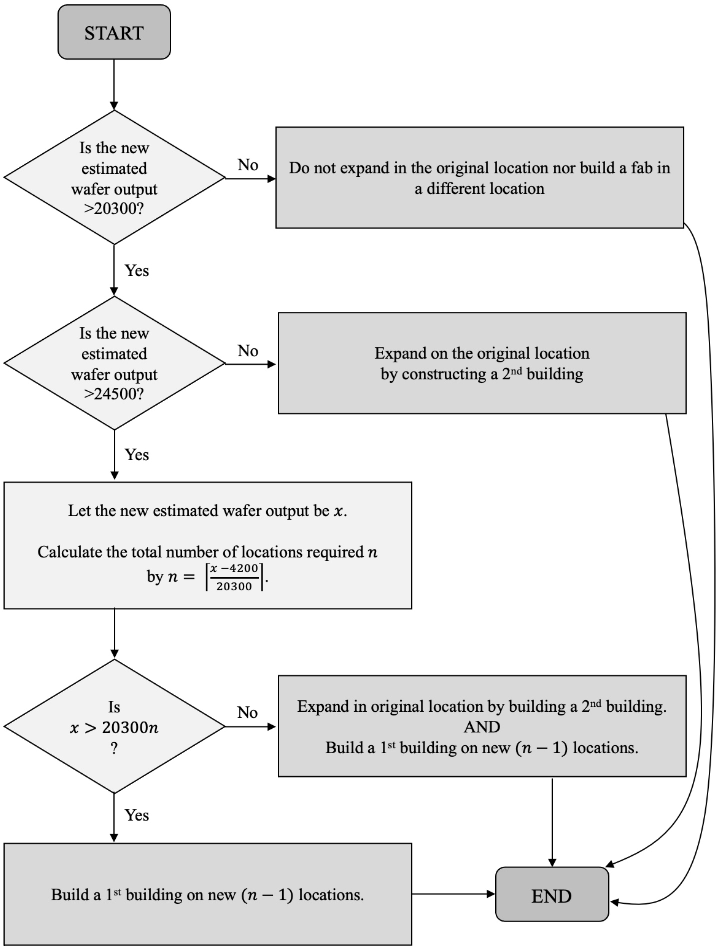


Thus, from this table, it is cheaper to build a new fab than expand on an existing fab. This scenario will come up every $20300n + 4200$, where n is a positive integer. This decision framework will loop between these two scenarios for a wafer output of above 20,300.

This gets coded into a programming function (refer to Appendix for the exact function) which outputs the total additional CAPEX required.

7. Delivery Time & Wafer Output: Fab Expansion versus Fab Construction

From the CAPEX graph and consideration of the decision framework stated, a decision tree (in a flowchart style) can be derived to guide the leadership team on the decision of whether to expand an existing fab or build a new fab. This is shown below:



Hence, it depends on the estimated wafer output to determine the decision.

III. Fab Expansion Factors Analysis

The decision to expand the fabrication plant must take into consideration many factors. Besides delivery time and loading that are discussed and calculated in part II, there are other critical factors that need to be considered: Expectation of returns, the ability to forecast demand and technology.

1. Expectation of Returns: Break-even Analysis

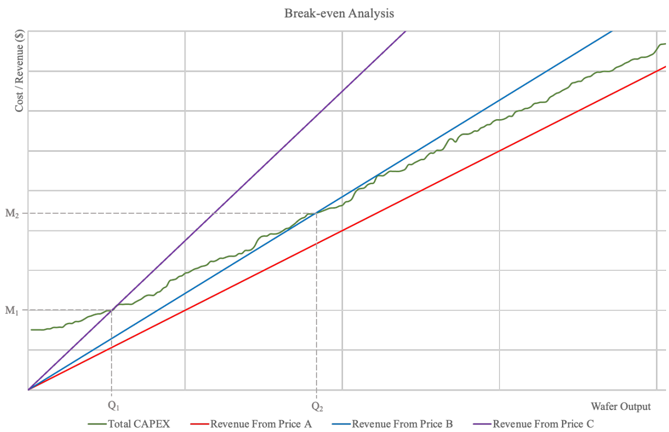
Investing large sums of money in expanding the current fab can never be justified unless there is enough time to pay back the investment (Stray et al, 2006). To analyse the future profit of the decision, the break-even point is used to study the expected return of investment based on product sales. To simplify the situation & facilitate our analysis, we assume the wafer output equals to sales, i.e the company does not have an unmet supply

Break-even Analysis is to investigate the point where a business's sale has generated enough income to cover the total of fixed costs and expenses, called Break-even Point (BEP) and can be computed by:

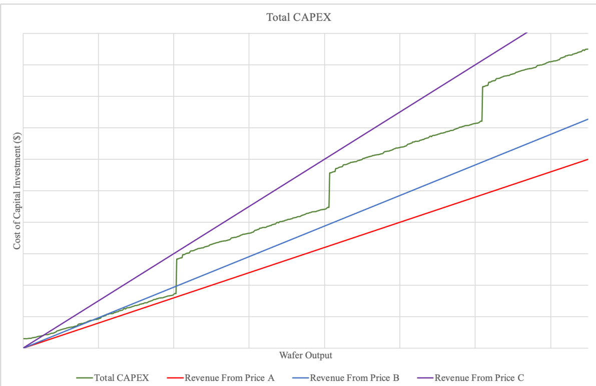
$$Break\ Even\ Point\ = \frac{FC}{P\ -\ VC}$$

where FC is fixed cost (\$), P is unit sale price (units) and VC is variable cost (\$). Therefore, we aim to lower the BEP because it ensures greater certainty of profitability.

To lower BEP, we can either increase the selling price or increase the sales. Increasing selling price is most likely undesirable, although it can help increase the revenue by much, because the higher price may lower the ability and willingness to buy of customers, thus decreasing sales. Hence, we analyse the scenario when companies attempt to ramp up production for a potential increase in sales.



Costs of processing semiconductors consist of overhead, material costs, equipment costs & labour costs (Gajera, 2006). To simplify our calculation of costs incurred in the process, given the Data Set, we assume material costs and labour costs are negligible (compared to billions of dollars invested), and take into consideration equipment cost & overhead cost as total CAPEX on machines purchase and building construction. Adopting the function of CAPEX as wafer output varies (refer to part II.6), coupled with 3 linear functions of revenue of 3 different prices A, B, and C (A < B < C), the following graph demonstrates the 3 different break-even points. Given the wafer sales as a variable, the greater the selling price, the lower the intersection points, the lower BEP. To generate profit, the company must constantly sell more BEP.



However, when expanding the fab, the requirement of delivery time less than 2 minutes to ensure maximised utilisation of machines results in a maximum number of machines. With a cap for machine capacity per week, wafer output produced in this case is limited to 26400 units.

The function of revenue is linear: its derivative is a constant assuming that the selling price does not ramp up with wafer sales. Thus, the increase in revenue per selling unit is constant. However, the graph for total costs CAPEX (excluding labour costs, material cost, and part of overhead costs) is observed with a sudden huge increase when the limits of wafer output at one fab is exceeded. To increase the output to potentially increase sales, another giant investment of billions in building new facilities and purchase of machines once again occurs. Its derivative, representing the change in total costs, in this case, increases rapidly per wafer unit sold. Therefore, losses are more likely than benefits as the increase in cost is more than the increase in revenue per unit sales.

In addition, it is important to be aware that many variables of costs have been neglected in this model and the cost of materials, increasing process complexity, labour costs, costs of building & facilities under present stringent standards is ever-increasing (Gajera, 2006) with regards to time. Hence, in reality, the actual total costs graph will shift higher, resulting in an even higher break-even point, implying the company must sell an even higher amount of products to generate profit, which may either be impossible due to limitation of wafer output or even if possible - only when the company decides to build another fab yet the cost undoubtedly outweighs the profit.

Therefore, a company should do a break-even analysis to learn which quantity of production is profitable, providing that there is no unsold unit produced (sell rate = 100%, there is no surplus of products produced), by calculating the costs that the company is faced with, the current pricing strategy of products. In the case of fab expansion, if BEP is low, it is financially sound to carry out the plan. If BEP is high, considerations of expected return on investment should be studied carefully.

2. Demand Projection Forecast

COVID-19 pandemic has caused a surge in demand for gadgets and electronic devices. Since semiconductors and chips are the brains of these modern electronics, an increase in demand for these technologies means an increase in demand for semiconductors (Yinug, 2021). However, when demand exceeds supply, a shortage occurs. The shortage of chips and semiconductors in the market will prompt companies to expand their capacity for the production of these products. As market demand increases, and if existing manufacturing plants are close to their maximum capacities, corporations face decisions about where and how to expand their production capacities (N. Julka et al, 2007). Hence, the ability to forecast demand plays an important role in a fabrication plant expansion.

a. Context

Demand forecast plays a critical role to determine capital investment for capacity planning. As semiconductor products in a consumer era become more diversified with a shortening life cycle, demand forecasting also becomes more complex and difficult (Chin, Cheng, Peng, 2008). Demand forecast plays a critical role to determine capital investment for capacity planning to improve capacity utilization and capital effectiveness (Wu and Chien, 2008). Moore’s Law has driven the semiconductor industry to keep technology migrations and wafer enlargement to maintain the cost reduction per transistor and the growth of the semiconductor industry (Leachman, Ding, and Chien, 2007). In other words, Moore's Law shortens the technology product life cycle and product substitution time. On the other hand, consumption of diversified semiconductor products is affected by various economic factors, which lead to demand uncertainty and increasing risks of capacity shortage and/or surplus in the demand forecast.

How to plan the capacity is an important decision for companies. However, capacity planning relies on demand forecasting. If demand forecasting values are overestimated than the actual values unfolded later, capacity cannot be utilized efficiently. It might lead to idle capacity and waste. When demand forecasting values are underestimated than actual values unfolded in the future, capacity will not be sufficient to fulfill the demands then. It might lose the orders or customers (Chien, Cheng and Peng, 2008). Hence, there is an urgent need to consider demand forecast ability when it comes to the expansion of fabrication plants.

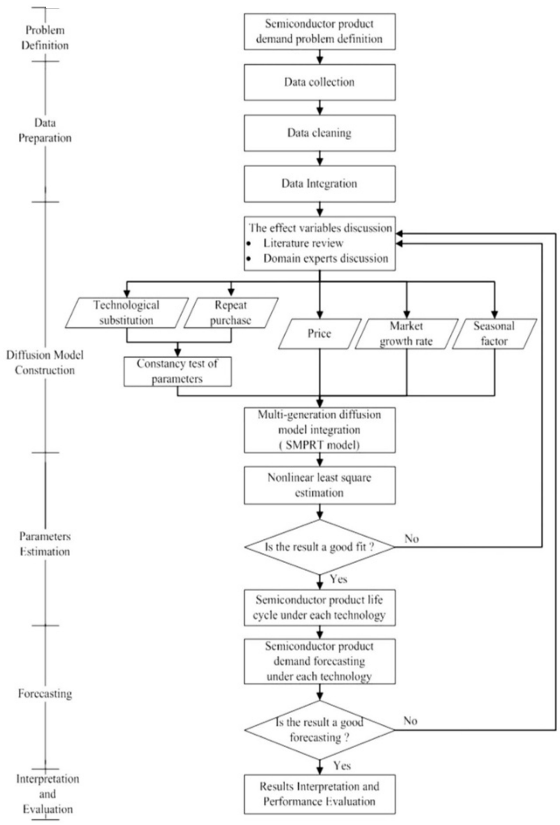
b. The Effect Variables in the model to forecast demand

There are five factors considered in this model of demand forecast including technological substitution, repeat purchases, price, market growth rate and seasonal factor. When considering expanding fab due to the increase in demand for semiconductors, it is necessary to take these factors into account in order to reach the best decision. In this scenario, we will use the demand forecasting model of SMPRT, developed by Norton and Bass in 1987:

i. Technological substitution effects

As a result of Moore's law, the semiconductor industry developed rapidly. Newer technologies are continually introduced to the market and are always superior due to newer technologies with attached applications and functions, hence newer technologies will replace older ones step by step. The introduction of newer technology also widens the market potential and affects the buyers of the older technology to buy the newer technology to substitute the older ones. Most forecasting methods only focus on the new product itself and ignore the older generation products that might compete with new products. The single generation diffusion models or other forecasting methods are not suitable for semiconductor products. It is essentially technological innovation for the new products of the semiconductor industry. It needs to consider both diffusion and substitution for semiconductor products in this study and therefore multigeneration diffusion models are feasible for semiconductor products.

Product demand forecasting framework



ii. Repeat purchases

This model considers the effects of repeat purchase, as consumers do not purchase products in single-unit quantities.

iii. Price effects

Price is a pivoting factor to affect customers what to buy and therefore the price effect of multigeneration products is important. The pricing strategy considers not only the stages of the product life cycle but also the substitution of newer generation products. Higher product price means lower quantity demanded and vice versa. As the newer generation products are introduced to the market, the price of the newer generation products will affect customers to decide what to buy. If the expected future price is changed, the behaviors of the customers also change. For semiconductor products, the price goes down quickly in the initial stage of the products and varies in the latter stage.

iv. Market growth rates

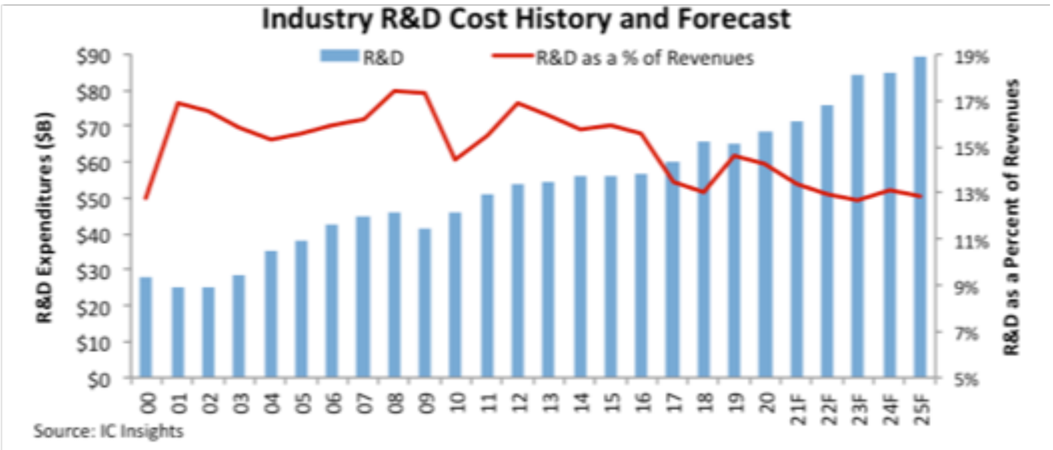
Growth rate is a factor to describe the social environment. The variation of customer behaviors is affected by the growth rate. When the growth rate is rising, the demand might increase.

v. Seasonal factors

Semiconductor products applied to various industries such as PC manufacturing and communication. However, the sales of PC may be affected by seasonal factor.

Hence, with the proposed model, it is possible to predict the demand, assuming that demand increases linearly with time. Thus, this model would help the company assess whether there is a need for expansion of the fabrication plant in order to increase the supply of semiconductors in the market.

3. R&D: Advancement of Technologies



According to IC Insights' new 2021 edition of *The McClean Report—A Complete Analysis and Forecast of the Integrated Circuit Industry,* research and development spending by semiconductor companies worldwide is forecast to grow 4% in 2021 to $71.4 billion after rising 5% in 2020 to a record high of $68.4 billion. With billions of dollars spent in R&D, it is doubtless that technologies play an essential role in any semiconductor companies.

The graph above plots semiconductor R&D spending levels and the spending-to-sales ratios over the past two decades and IC Insights' forecast through 2025. It can be seen that there is a clear increasing trend in the amount of money spent on R&D, yet a decreasing trend in the values of R&D as a percentage of Revenues. This indicates that the higher investment in technologies, the higher the revenue of the companies. Thanks to the investment in R&D, new technologies are created. For the new technologies created to be mass-produced, it will take an amount of time. For example, the new chipset is produced by key Apple supplier Taiwan Semiconductor Manufacturing Co (TSMC), the world's largest contract chipmaker, using the latest semiconductor production technology, known as 5-nanometer plus, or N5P. Producing such advanced chipsets takes at least three months. While waiting for the new chips to be mass-produced and widely used, the companies still need to keep up with the production of the previous technologies. As a result, technology is seen as a key factor in expanding the fabrication, since the companies need to invest more in facilities to produce the technology. According to CNN, "Most computer chips powering devices today use 10-nanometer or 7-nanometer process technology, with some manufacturers producing 5-nanometer chips". As a producer of the chips, TSMC, while keeping up with the demands of 10-nanometer and 7-nanometer chips, needs to expand to produce 5-nanometer chips. For instance, while the iPhone 12's A14 chip requires a 5 nm chip, a 7nm chip is still required for iPhone 11's A13 chip and iPhone XS's A12 chip. As a result, in order to produce 5 nm chip, TSMC announced that it is moving forward with plans to build a $12 billion chip plant in Phoenix in order to mass-produce chips fabricated with a five-nanometer process by 2024. Hence, when expanding fabrication, technology is one of the most critical factors in the decision-making process.

IV. Assessment of Case Study: Micron Singapore

Micron Singapore is a good candidate for expansion, according to the three factors that we consider: demand, technology and break-even point.

In terms of demand, Mr Heng Swee Keat, Deputy Prime Minister and Minister for Finance, said: "No doubt the global semiconductor industry is experiencing headwinds this year due to global market uncertainties. But these headwinds should be viewed in the context of the 'semiconductor super cycle' which took place in the preceding few years - where global demand grew by more than 35%." Singapore accounts for 11% of the global market share for semiconductors, which further suggests the increasing demand for semiconductors from Singapore (The Straits Times, 2020). To meet this demand and to eliminate the shortage caused by the surge in demand for semiconductors, it is necessary for semiconductor manufacturers in Singapore like Micron Singapore to increase their capacity output by expanding their fabrication plant.

Besides, with the advent of 5G technology, memory demand is expected to increase further, which requires even more semiconductor. As a result, Micron Singapore can cross "demand forecast" off the checklist when considering expanding. In terms of technology, Micron, as one of the major suppliers of DRAM and NAND memory chips and a world leader in innovative memory solutions that transform how the world uses information to enrich life, needs to produce advanced 3D Nand flash memory chips, which are used to produce solid-state drives that are used in smartphones, tablets and computer (The Straits Times, 2020). As a result, it is essential for Micron Singapore to expand its facilities in order to satisfy the demand for the latest technologies.

Our assessment would be much more accurate if quantitative analysis (Break-even Analysis) is carried out for more in-depth insights, besides qualitative analysis of factors such as demand & technology. Due to the non-disclosure of data of Micron in Singapore specifically, financial report & production database, we are unable to assess its ability to expand due to the inability to generate the break-even analysis model. We believe that given data sets about production capacity, processing cost of fabs, a more accurate analysis would be possible, considering the revenue Micron Singapore generates, fixed cost of manufacture, and variable costs incurred. Yet, based on the fact that Micron has multiple fabs in Singapore (5 fabs, only 3 fabs producing DRAM & NAND), it can be inferred that Micron Singapore is making good profits. This suggests Micron Singapore's increasing output, thus, expanding the fab would be necessary in order to create more revenue, hence reaching the break-even point or creating more profit. As a result, Micron Singapore is a good candidate for expansion.

V. Conclusion

To conclude, as the production in plants in the manufacturing network reaches maximum capacities, the need to decide upon the investment for capacity expansion also arises (N.Julka et al, 2007). When expanding the current fab, the company may need to compromise delivery time and wafer output yet benefit from the current working machines; while, building a new fab may incur a lower cost of building but a greater cost of machines purchases. Due to uncertain demand and limitation of wafer output produced by each fab even after building and expansion, companies should employ the break-even analysis as part of the decision framework. With that, the certainty of profitability of capacity expansion decisions will be guaranteed.

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VIII. Appendix

Each of these files will show the working for each section.

<table>
<tr><th>Section</th><th>Files to Refer Working to</th></tr>
<tr><td>II.2 Capacity of Machine at Each Step</td><td>P_VaaT_Supporting_Document_QuestionDataset.xlsm
P_VaaT_Supporting_Document_QuestionDataset_Flow.csv
P_VaaT_Supporting_Document_QuestionDataset_WSData.csv</td></tr>
<tr><td>II.3 Number of Machines & Capital Investment</td><td rowspan="3">P_VaaT_Supporting_Document_MachineDetails.ipynb
P_VaaT_Supporting_Document_machine_summary.csv
P_VaaT_Supporting_Document_machine_summary.xlsx
P_VaaT_Supporting_Document_data_generated (folder)
P_VaaT_Supporting_Document_graphs.pdf</td></tr>
<tr><td>II.4 Wafer Output & Delivery Time</td></tr>
<tr><td>II.5 Wafer Output & Footprint Requirement</td></tr>
<tr><td>II.6 Wafer Output & Total Capital Investment</td><td>P_VaaT_Supporting_Document_CAPEXCalc.ipynb
P_VaaT_Supporting_Document_capex.csv
P_VaaT_Supporting_Document_capex.xlsx
P_VaaT_Supporting_Document_graphs.pdf</td></tr>
<tr><td>II.7 Delivery Time & Wafer Output: Fab Expansion versus Fab Construction</td><td>P_VaaT_Supporting_Document_decision_tree_flowchart.pdf</td></tr>
</table>