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# Capacity estimation model of cluster tool in wafer fabrication

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***Abstract:*** *Semiconductor manufacturing is a cost intensive industry particularly for modern 300mm manufacturing factories. Thus, production yield improvement is the most crucial issue to the manufacturing productivity correspondingly. Cluster tools are regarded as mainstream in modern semiconductor manufacturing factories over the past decade which dominated around 60% of production machines. Due to integrated by several components in a module and operated as a small factory, this kind of equipment increases the difficulty of production planning and shop floor control significantly because of complicated machine configurations. Moreover, for some small and middle scale semiconductor factories, managers will consider to combine un-relevant processes into one machine due to machine numbers and cost constraints. Thus, it will turn the difficulty of capacity estimation and planning into arduous challenge. In this work, the model of short term capacity planning for cluster tools is established. Three modules, WIP profile estimation, WIP schedule arrangement and capacity requirement calculation, are developed in this model. The concept of turn ratio is used to estimate the WIP penetration and forecast the WIP profile within a short time period. In order to reach the production goal of maximum output without exceeding time limit of product,* $E_c$ *value of WIP is formulated. Based on WIP profile and* $E_c$ *value of WIP, the expected recipe combination working on the equipment can be decided and the required capacity can be calculated as well.*

***Index Terms:*** *Wafer fabrication, Cluster tool, Capacity estimation, Turn ratio, Time limit.*

## I. INTRODUCTION

Semiconductor industry in Taiwan arise a tremendous excellence over the past decades. It not only builds up the advanced technology benchmark in the world, but also plays an important lifeline for Taiwan's economic development. Nonetheless, in addition to the characteristics of capital, labor and technology intensive, the complex production environment, huge operations steps and the pursuit of high equipment utilization make the production management of semiconductor manufacturing more complicated than other industries. Therefore, managers need face many unexpected challenges in management and operations (Rulkens 1998, Robinson 1999). Furthermore, with the rapid migration of advanced process technology, the investment cost of new process equipment is also increased exponentially. Managers always hope to improve their competitive strength without expanding the new machine, and find the best production control measures through various management methods to achieve the better productivity and enhance their competitiveness.

Contemporary semiconductor manufacturing by increasing cluster tools, each of clusters consists of several single-wafer processing chambers, to disperse semiconductor fabrication processes, shorten cycle time, speed up process development, and get better yield with less contamination (Perkinson et al. 1996, Liao 2010). The last decade or so has been major change in the main stream of production equipment are cluster tools, which almost dominate 60% capacity of modern wafer fabrication factories and continuous to increase for more advanced technology. Generally, the vacuum etching and thin film process in semiconductor manufacturing are using cluster tools. There are several components including load ports to loading & unloading FOUPs, ATM and VTM robots, vacuum chambers (Load locks) and single-wafer process chambers in a cluster tool as Figure 1, and it operates as a small factory. Since most of components are shared and associates with different recipe combinations, the capacity estimation is complicated. In terms of capacity estimation, fabs can only operate in an estimated way for the cluster tools in the past. Moreover, due to the gap between the upper-level capacity estimation and the actual operation of the site, cluster tool even jumped into a bottleneck in the small or medium scale of factories. Accordingly, how to construct a capacity estimation model of cluster tools is very important for the modern semiconductor factories indeed.

The purpose of this study is to propose a capacity planning model which includes three modules, WIP profile estimation, WIP schedule arrangement and capacity requirement calculation. Furthermore, due to the differences of resolution and length of time horizon, the capacity is planned only for the short term view. The concept of turn rate is used to estimate the WIP penetration and forecast the WIP profile within a short time period. Based on WIP profile and the performance table of recipe combination developed in the previous study, the expected recipe combination working on the equipment can be decided and the required capacity can be calculated as well.

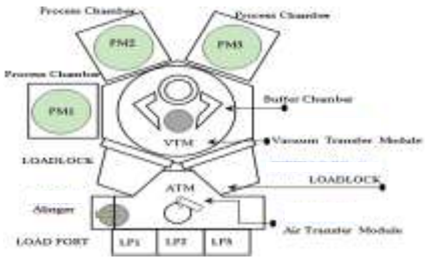


Figure 1: Cluster Tool

## II. LITERATURE REVIEW

In the light of capacity estimation and planning, it generally refers to medium and long-term capacity planning. In the past, many scholars have proposed various capacity planning models for the semiconductor manufacturing industry, and most of them applied queueing network, mathematical analysis and mean value analysis to analyze the number of machines required for each machine group (Iwata et al., 2003; Walid and Gharbi, 2002; Chou and You, 2001; Romauch & Hartl 2016; Ortner 2008; Wood et al., 1994). In addition to fulfill the future needs, the purpose of capacity planning is related to the goal of shortening production time, minimizing production costs, and improving customer satisfaction (Iwata et al., 2003). However, these studies have not taken future uncertainties and equipment investment risks into accounts. The industries such as semiconductor manufacturing, which has high demand uncertainty and investment risks, such planning results are bounded to be insufficient. It is rarely studied in the past researches for short-term capacity estimation, mainly because other types of machines in the general industries or fabs are extremely easy to estimate and do not pose management problems. Because of paucity of research data, it is not possible to come to any definitive conclusions for production plan of cluster tools. This type of machine is structurally more complex than other types of machines which can be treated as a small factory, thus, the internal scheduling must be completed in capacity estimation. The production planning of the upper class or the short-term on-site scheduling will not run smoothly if lacking of accurate capacity estimation. The reason why such machine capacity is extremely difficult to estimate is that it has many internal scheduling limitations and difficulties, such as: multiple manufacturing processes, parallel reaction chambers, no wafer temporary storage area between the reaction chambers and wafers. All processes are processed to return back to Load Lock and the residence time limit after completion of the reaction chamber (Kim et al. 2016, Lee 2008). As mentioned above, many researches focused on internal schedule of single-chip multi-reaction chambers that were partially considered the scheduling limitations and difficulties only in the past. (Venkatesh et al. 1997, Wu et al. 2011, Qiao et al. 2013, Lee et al. 2007, Zuberek 2004). Venkatesh et al. proposed a steady-state model to analyze the output of a single-piece multi-reaction chamber machine with dual arms. This mode divided the system into two states: the bottleneck is in transit and the bottleneck is in the reaction chamber portion of the process. Some scholars used Petri Net theory to study the internal scheduling of single-chip multi-reaction chamber machines (Wu et al. 2010-2013, Qiao et al. 2013, Lee et al. 2007, Zuberek 2004). Wu et al. used Petri Net to propose a series of scheduling logic theory to analyze the product cycle time and schedule for different repetitive machining under time constraints. These modes and schedules were all analyzed for steady-state and periodic procedures instead of authentic operation situation. Considering the actual machine operation, there will have many cases where the empty machine starts running and the recipe changes from time to time. These complex patterns will induce the inaccuracies of these modes without any exception. In addition, some scholars have explored non-cyclical procedures for scheduling analysis (Kim et al. 2015-2016, Wikborg & Lee 2013). Kim and Wikborg proposed an effective set of logic to optimize robot's non-cyclical work order, and also consider the robot's anti-locking policy. However, such theoretical application may not be effective if the bottleneck does not fall on the robot. Therefore, it seems no any adequately solution for practice although many methods have been proposed.

## III. CAPACITY ESTIMATION MODEL

As stated in the background and motivation, it is necessary to move forward to a different kind of planning model to fit the practical situation. Many studies have focused on the scheduling of the machine's internal operations, thereby calculating the throughput of the machine in the past decades. Up to date, because the structure of cluster tools are more complex and operate like a small factory, internal scheduling must be completed in capacity estimation. Furthermore, due to the diverse and complex structures of the machine portfolio, and the scheduling is also a problem of NP hard, most of the research has simplified the reality and has a gap with the actual operations. Hence, it is difficult to apply this solution in practice. In this study, a model that is really suitable for the practical use is proposed, and its applicability can be used in the short-term scheduling. In general, the products targeted by the short-term plan are usually on the production line or will be released shortly which means the situation is very clear. At this point, the resolution must be improved in order to have accurate planning. Observably, it can be revealed that the factors which influence the accuracy of planning in capacity planning are the input data and the methods used in the planning model. The input of capacity planning is nothing more than the product mix to be produced and the amount of capacity that can be provided per unit of time. Regarding to the cluster tool if the processing combination is determined, the required capacity can be estimated. Usually, the processing combination of the machine is determined by the WIP profile in front of the machine at that time. Based on these concepts, there are three functions should be included in a capacity estimation model of cluster tool, forecasting the future WIP profile, arranging the processing combination and calculating the required capacity. The followings are the details of these modules.

### A. WIP profile estimation

Regarding to the short-term capacity planning, the most important factor for a cluster tools is the processing combination of the machine. When the processing combination of the machine is determined, the required capacity can be determined, and the unit time capacity of the machine will also be found out as well. The processing combination of the machine is determined by the distribution of the products in front of the machine at that time. The site manager can only choose the existing WIP and decide the processing combination. The decision of this processing combination is structured to achieve the production goal, including maximizing output, maximizing delivery rate, and minimizing time limits. As everyone knows that the scheduling goal in this station is mainly to achieve maximum output without exceeding time limit of product. Therefore, the short-term processing combination should be combined these two expectations accordingly. The procedures of WIP estimation module is described below.

Step 1: Get the data

Capture WIP data and Technology Turn Ratio（TR）of WIP

Step 2: Project WIP status at steady state

In order to provide the scheduling mode for the next stage, the short-term WIP project will be set the Time bucket to 3 hours, while the Time horizon is 7 days. The following is the equation of WIP projection.

$$\mathrm{S_w} \in \left(\sum_{\mathrm{k=S_{wn}}}^{\mathrm{S_w}} \frac{1}{\mathrm{TR_{tk}}}\right) = 7 \qquad (1)$$

Where,

$\mathrm{S_w}$ ： the step of WIP w

$S_{wn}$ : current step of WIP w

$TR_{tk}$ : turn ratio of step k of Technology t

Step 3: Estimate the time bucket of WIP and new released lot which will be processed by cluster tool

In this step, the forward scheduling method is used to project the time bucket which the WIP and new released lots need to process on the cluster tool. The calculation formula is as follows.

$$TB_{wij} = \sum_{k=S_w}^{S_{ij}} \frac{1}{TR_{tk}} \quad (2)$$

Where,

$TB_{wij}$ : the time bucket of WIP w for the jth processed on cluster tool i

$S_{ij}$ : the step for the jth processed on cluster tool i

Step 4: Summarize all WIPs on the same time bucket within 7 days

Summarize the WIPs in front of cluster tool for each time bucket within 7 days. That is the demand of each cluster tool by time bucket.

## B. WIP processing schedule arrangement

Eventually, the production performance of cluster tools will be affected by the processing combination. Therefore, in order to arrange processing combination properly, WIP profile is estimated in the previous module. Furthermore, the major purpose of short-term capacity plan is to check if the capacity is sufficient, and whether it is necessary to ask for support or not, so it should be arranged according to the current situation of the current machine.

Consequently, in the short-term planning, the WIP in front of the machine is the real WIP to be processed within 3 hours. Since the production goal is maximum output without exceeding time limit of product, $E_c$value of WIP is developed as an index of WIP processing priority. The formula of $E_c$ is as follows.

$$E_c = \frac{\sum_{i=1}^{n} E_{ic}}{n} \quad (3)$$

$$E_{rc} = \frac{SWPH_{rc}}{TWPH_r} \quad (4)$$

$$TWPH_r = \frac{1}{PT_r} \quad (5)$$

Where,

$E_{rc}$ : Efficiency of Recipe r under process combination c

$SWPH_{rc}$ : simulated throughput of Recipe r under process combination c

$TWPH_r$ : theoretical throughput of Recipe r under process combination c

$PT_r$ : process time of Recipe r

$E_c$ : efficiency of process combination

$E_{ic}$ : efficiency of Chamber i under process combination c

n : number of Chamber in a machine

## C. Capacity requirement calculation

As for the capacity estimation, required capacity calculation will be based on the processing combination of the machine to estimate the demand capacity. The following is the description of the steps for capacity estimation.

Step 1. Calculate the required process time

$$DH_m = \sum_{r=1}^{mr} \frac{QTY_{rc}}{TWPH_r \times E_{rc}} \quad (6)$$

Where,

$DH_m$ : demand hour of WIP in front of cluster tool m

$QTY_{rc}$ : wafer quantity of Recipe r under process combination c

mr : recipe number of WIP in front of cluster tool m

Step 2. Calculate the required machine quantity in each time bucket

For the short-term planning, the required machine quantities for every 3 hours are calculated.

$$TBM_{im} = \frac{DH_{im}}{TB_i \times A_m \times n} \quad (7)$$

$$A_m = \frac{MTBF_m}{MTBF_m + MTTR_m} \quad (8)$$

Where,

$TBM_m$ : required quantity of machine m in Time Bucket i

$TB_i$ : Time Bucket i,

$A_m$ : Availability of machine m

Step 3. Calculate the required machine quantity

The actual required machine quantity will be the maximum quantity of all required quantity of time bucket

$$M_m = Max(TBM_{im}) \quad (9)$$

Where,

$M_m$ : required quantity of machine m

## IV. CONCLUSION

Cluster tools are not only numerous but also very important in fabs. In addition, due to its complicated structure, it is very difficult to improve the performance from the upper level of production capacity planning to shop floor management and control. Although some scholars have proposed a lot of researches on such machines in the past, there are many assumptions and there are many differences with the limitations of field operations, and lead to the difficulties in the application of practice. Therefore, how to construct a capacity estimation model for cluster tool is more important for the fab. In this study, a short-term capacity planning model is developed, including three module which are WIP profile estimation, WIP schedule arrangement and capacity requirement calculation. The coming WIP can be forecasted in the WIP profile estimation module. Based on the estimated coming WIP and production goals, WIP can be well scheduled by the WIP schedule arrangement module. Finally, the capacity requirement can be calculated accurately based on the arranged schedule. The results strongly support the viability of this planning model. Manager can easier plan the capacity of shop floor and make the production activities smoothly and effectively by applying this model.

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