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Long-term tool elimination planning for a wafer fab

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Abstract

Wafer manufacturers must make decisions regarding tool elimination due to changes caused by demand, product mixes, and overseas fab capacity expansion. Such a problem is raised by leading semiconductor manufacturers in Taiwan. This paper is aimed at developing a sound mechanism for tool portfolio elimination based on determining which equipment can be pruned. In the proposed mechanism, product mix, wafer output, capital expenditure, tool utilization, protective capacity, and cycle time are taken into the overall evaluation. This paper develops an integer programming model to avoid trial-and-error and to obtain the optimal solution. Compared to the current industry approach, the results show that the proposed mechanism can effectively identify the correct tools for elimination with a large capital savings and little cycle time impact.

Keywords: Tool portfolio; Capacity planning; Semiconductor

1. Introduction

Modern wafer fabrication facilities being built today by such companies as Motorola, Intel, and Advanced Micro Devices require excess of 1 billion dollars investment, chiefly due to the high cost of machinery and the need for a clean room (Bard, Srinivasan, & Tirupati, 1999). More than 60% of the total cost is attributed to the equipment alone. Making efficient use of equipment is therefore of great strategic importance, especially since profitability is determined by amortizing the cost of the facility over all chips produced (Bard et al., 1999). Thus, even a small improvement in the procurement decisions could have a large impact on the manufacturer's performance (Swaminathan, 2000). Practical experience in this industry indicates that a small capacity saving could result in millions of dollars in benefit per year (Wang & Lin, 2002).

Both 200 and 300 mm wafer manufacturers, especially multi-fab foundries, must make decisions regarding tool elimination due to the dramatic and frequent changes in the internal and external manufacturing environments. These changes often originate from demand, product mixes, and oversea fab capacity expansion. Such a problem is raised by leading manufacturers of semiconductors in Taiwan, who strongly require help in

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solving the tool elimination issue, making decision regarding tool disposal or transferring to support overseas fab capacity expansion.

As different equipment types and corresponding quantities are eliminated from a fab, different influences will result in both fab production performance and the company-wide capital expenditure, or fab cost structure. This shows that poor tool elimination planning will lose cost competitiveness in the market and impact production performance, even if a fab implements sound scheduling plans and dispatching rules. Consequently, a sound mechanism that can evaluate the impacts of tool elimination is needed to provide more suitable information for management decision making.

Tool portfolio planning is a very complex problem. Quickly obtaining the optimal solution is very difficult. Yang (2000) proposed a procedure and decision-making criteria to make capacity expansion plans for a Taiwan Semiconductor Manufacturing Company (TSMC) fab. Witte (1996), Wu, Yang, and Liao (1998), and Chou and You (2001) pointed out that many planners in industry often use static models for tool portfolio planning due to fast computation and ease of use. Alternatively, most authors used heuristics or omitted some of the important characteristics to solve the complex and difficult problem in their researches.

Simulation, heuristic, queuing network, and combinations of these programs are common techniques used to solve the tool portfolio planning problem in the literature. Chou and Wu (2002) and Wu et al. (2005) made the comparisons of advantages and disadvantages between simulation and queuing network. Queuing models require a very short time to run and provide the flow time, utilization, and WIP performance information with modest accuracy (Bretthauer, 1996; Chou, 1999; Chou & You, 2001; Chou & Wu, 2002; Connors, Feigin, & Yao, 1996; Wu, Hsiung, & Hsu, 2005; Yoneda et al., 1992). Simulation is usually used to analyze operation dynamics at very detailed levels but needs much of an effort on construction and maintenance for evaluating many alternative portfolios. Hence, it is not suitable for the early stages of tool portfolio planning (Chen & Chen, 1996; Grewal, Bruska, Wulfm, & Robinson, 1998; Mollaghsemi & Evans, 1994). Besides, heuristic and combinations of these programs are used to consider more important characteristics and provide more information under different manufacturing environments and complexities (Bard et al., 1999; Chung & Hsieh, 2004; Donohue, Hopp, & Spearman, 2002; Iwata, Taji, & Tamura, 2003; Neacy et al., 1993; Swaminathan, 2000, 2002; Wang & Lin, 2002).

Table 1 summarizes the recent literature on new tool portfolio planning, and makes a comparison of the methodologies used and characteristics considered in 23 reviewed papers. On-time delivery and cost are two critical factors in deciding competitiveness in the semiconductor industry, 14 out of the 23 papers use cycle time as the primary consideration and 15 out of 23 papers use budget for new tool planning. However, only 8 out of the 23 papers use cycle time and budget characteristics simultaneously.

The above literature review reveals that many studies focused only on the new tool portfolio planning. The literature on tool elimination research for fab factories is insufficient in model development, even though this is critical to the industry.

This paper is aimed at developing a mechanism for making decisions regarding the tool elimination in a semiconductor wafer fab. Taking into consideration the product mix variations and wafer output targets, the proposed elimination mechanism evaluates which equipment can be pruned according to core competitive elements in production management, namely, output, delivery, and cost. For more practical considerations, engineering, and layout issue factors are also presented in the proposed mechanism.

The rest of this paper is structured as follows. The following section presents an approach for tool portfolio elimination. Section 3 presents a numerical example based on the actual data collected from a wafer fabrication factory situated in the Science-Based Industrial Park in Taiwan. Conclusions are made in Section 4.

2. A mechanism for tool portfolio elimination

2.1. Basic principle and overall flow

This problem is raised by leading manufacturers of semiconductors in Taiwan, who strongly require help in solving the tool elimination issue due to the dramatic decreases in low-end technology demand at existing 8″ fab. At the same time, a new factory for producing low-end products is planned to setup in other country, it seeks for any possible tool sources from this existing factory in order to reasonable deployment of assets

Table 1
A summary of the recent literature on new tool portfolio planning

	Methodology	Recent literature	Major characteristics considered
Queuing Network	Simulated annealing	Yoneda et al. (1992)	Budget, WIP cost
	Marginal allocation procedure	Connors et al. (1996)	Cycle time, budget
	Branch & bound algorithm	Bretthauer (1996)	Budget
	Qualitative reasoning	Chou (1999)	Cycle time
		Chou and You (2001)	Cycle time, budget, throughput
	Utility function	Chou and Wu (2002)	Cycle time, budget, risk, throughput
	Genetic algorithm	Wu et al. (2005)	Cycle time, budget, demand uncertainty
Heuristic	Lagrangean relaxation, GB, SB	Swaminathan (2000)	Demand uncertainty, stock-out cost, budget
	Lagrangean relaxation, GB, SB	Swaminathan (2002)	Demand uncertainty, multi-period, stock-out cost, budget
	Genetic algorithm	Wang and Lin (2002)	Profit, budget
	BBCT	Chung and Hsieh (2004)	Cycle time, utilization
Simulation	STEP method	Mollaghsemi and Evans (1994)	Cycle time, utilization
	Response surface methodology	Chen and Chen (1996)	Cycle time, budget
	Static capacity	Grewal et al. (1998)	Cycle time, budget
Heuristic & Simulation		Neacy et al. (1993)	Cycle time
Heuristic & Queuing Network	Simulated annealing	Donohue et al. (2002)	Cycle time
		Bard et al. (1999)	Cycle time, budget
		Iwata et al. (2003)	Cycle time, budget, production cost
Linear Programming		Yang (2000)	Space, photo tool capability
		Hsieh and Lin (2002)	Cycle time, profit, photo tool capability
		Hua and Banerjee (2000)	Cost, budget
Stochastic Integer Programming		Eppen et al. (1989)	Demand uncertainty, profit, cost, risk
		Hood et al. (2003)	Demand uncertainty, multi-period, budget

among multi-sites. For example, the real case happens when transferring the equipments and products from the existing 8″ fabs in Taiwan to the new oversea 8″ fab in Mainland China.

To meet the changes in the new product mix and corresponding output target at existing 8″ fab, it is very helpful for semiconductor industry to determine which equipment needs to be kept in the existed fab and which equipment can be pruned for disposal or be transferred to an oversea fab being under expansion. This paper focuses on evaluating which equipment can be pruned. The detail scheduling of each output target plan is not within the scope, since it is the next planning level after making the decision on eliminable number of machines. However, the impact on cycle time is considered because of tool elimination.

To solve this complex and difficult problem, this paper proposes a mechanism for tool portfolio elimination based on the current fab's output plan that suffered low-end technology demand decreases. Fig. 1 shows the flow chart for the tool elimination mechanism. In the proposed mechanism, practical issues, product mix, wafer output, capital expenditure, tool utilization, protective capacity, and cycle time are taken into consideration.

When solving the tool elimination problem, more practical factors must be considered than the new tool investment problem. Initially, the proposed mechanism evaluates the execution feasibility from practical aspects, including engineering, layout factors, etc., to avoid invalid final elimination results.

Because different product mix and wafer output target plan will result in different equipment types and corresponding equipment quantities being eliminated, Step 1 is to input all the possible output plans based on the market department's forecast, including every possible product mixes and corresponding monthly output targets. Each output plan is generated from the viewpoint of aggregate level of hierarchical production planning

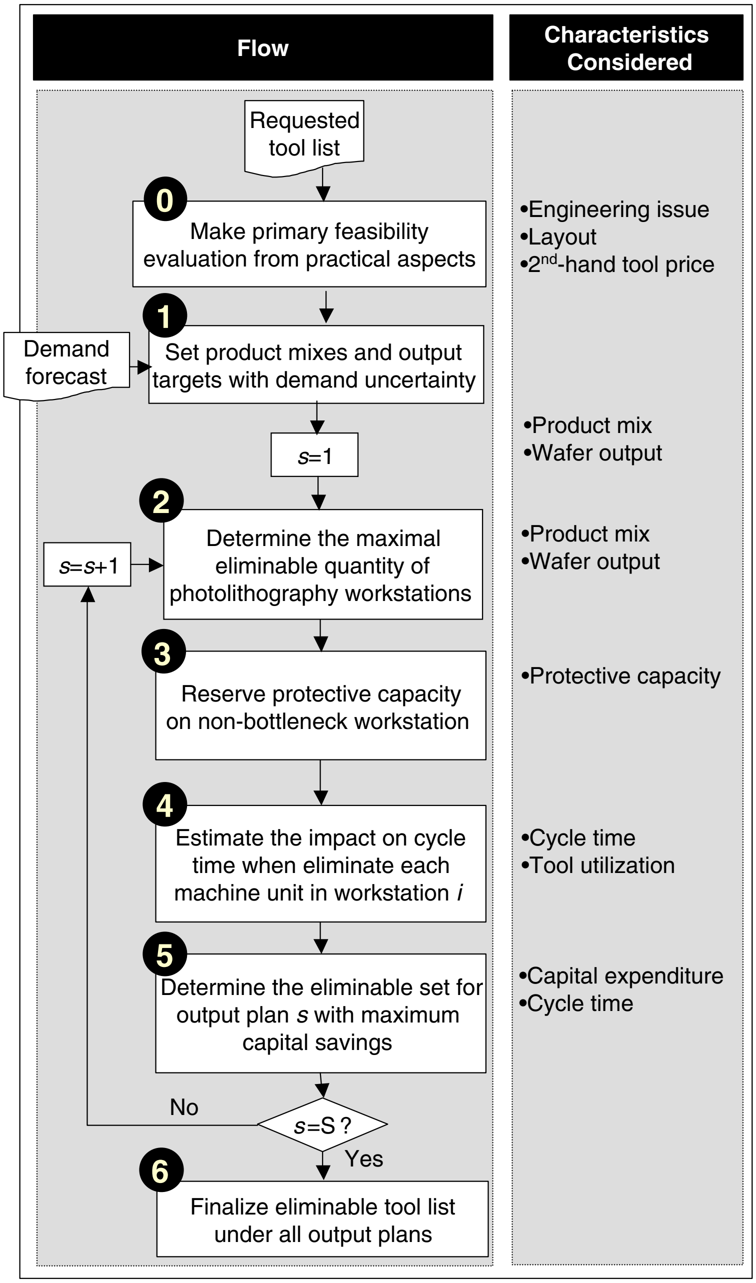


Fig. 1. Flow chart for the tool elimination mechanism.

(HPP). The planning horizon is 3 years for observing the possible demand variations during the ramp-down period.

Photolithography machine, the most expensive tool with the longest procurement lead time, needs to be placed at the special clean room to process the most critical operation for wafer fabrication with the characteristics of the highest re-entry frequencies. Hence, photolithography workstation is often defined as a bottleneck for the entire fab in industry and the literature (Shen & Leachman, 2003; Yang, 2000). In the proposed mechanism, the photolithography workstation is also defined as a bottleneck for the entire fab.

The process of wafer fabrication comprises a series of chemical treatments with the characteristic of re-entry, and no accessories are assembled during the processing. The structure differences between any two product types (or product families) are presented in their process plans in aspect of different re-entry times of each product type on different workstations, daily throughput of each workstation, yield of each product type, and monthly different output of each product type. For both bottleneck and non-bottleneck workstations, this paper considers these factors in deriving the required processing time of each workstation for fulfilling the product mix and corresponding monthly output target.

For reserving enough bottleneck capacity to fulfill the fab's output targets and product mixes set in the previous step, Step 2 calculates the required quantity of photolithography workstation and makes an estimation of the maximal eliminable quantity of this workstation. This step also helps Step 3 calculate the capacity requirements of non-bottleneck workstations based on output rate of bottleneck.

Based on theory of constraint (TOC), non-bottleneck workstations should reserve some capacity to protect the system output under system uncertainties. The mechanism proposes that the output rate of non-photo workstation must be greater than that of photolithography workstations and primarily filters the candidates for elimination in Step 3.

Shorter cycle time can improve cash flow, promote customer satisfaction, and reduce the risk of yield losses. Hence, the proposed mechanism takes cycle time into consideration in Step 4 and identifies the impact on production cycle time when one unit of specific equipment is eliminated.

As different equipment types and corresponding equipment quantities are eliminated from a fab, both the cycle time performance and the company-wide capital expenditure will be different. Hence, a sound tool elimination plan will win cost competitiveness in market and can maintain good cycle time performance. An integer programming model is developed to avoid trial-and-error effort in obtaining the optimal solution. Step 5 can effectively identify the eliminable set with a large capital savings and little cycle time impact. And the final step is to finalize eliminable tool list under all output plans being considered. Since the eliminated tool quantity proposed by the mechanism will be practically used for supporting the overseas fab or tool disposal decision-making in industry, this paper thus adopts the conservative way to ensure that the remaining capacity in each workstation should be enough to achieve each market demand scenario. Accordingly, the eliminable tool units are determined as the minimal eliminable number among all output plans. The detailed step-by-step descriptions are presented as follows.

2.2. Procedure of the tool elimination mechanism

Before describing the mechanism, all required notations are defined as below:

Notations

q_{photo}, q_i the original tool quantity for photolithography workstation and non-photo workstation i, respectively. $i = 1,\ldots,I$

$o_{s,d}$ the monthly output target for product d in output plan s. $d = 1,\ldots,D$; $s = 1,\ldots,S$

$f_{d,\text{photo}}$, $f_{d,i}$ the re-entry times of product d for photolithography workstation and non-photo workstation i, respectively

$t_{d,\text{photo}}$, $t_{d,i}$ the daily throughput of product d for photolithography workstation and non-photo workstation i, respectively

y_d the yield of product d

a_{photo}, a_i the tool availabilities for photolithography workstation and non-photo workstation i, respectively

$\text{RCAP}_{s,\text{photo}}$ the required monthly processing time of photolithography workstation in output plan s. $\text{RCAP}_{s,\text{photo}} = \sum_{d=1}^{D} o_{s,d} \times f_{d,\text{photo}} \div t_{d,\text{photo}} \div y_d$

$\text{RCAP}_{s,i}$ the required monthly processing time of non-photo workstation i in output plan s. $\text{RCAP}_{s,i} = \sum_{d=1}^{D} o_{s,d} \times f_{d,i} \div t_{d,i} \div y_d$

$\text{SCAP}_{s,\text{photo}}$ the monthly available capacity of one photolithography machine. $\text{SCAP}_{s,\text{photo}} = a_{\text{photo}} \times \text{days\_per\_month}$

$\text{SCAP}_{s,i}$ the monthly available capacity of one non-photo machine. $\text{SCAP}_{s,i} = a_i \times \text{days\_per\_month}$

$M_{s,\text{photo}}$ the tool quantity for photolithography workstation which can be eliminated in output plan s

$M_{s,i}$ the tool quantity for non-photo workstation i which can be eliminated in output plan s

$\left\lfloor \frac{x}{y} \right\rfloor$ the largest integer that is equal to or less than x divided by y

$\lceil\frac{x}{y}\rceil$ the least integer that is equal to or larger than x divided by y.

Step 0: Evaluate execution feasibility from practical aspects

If the candidate tool violates the following practical considerations, it will not be eliminated.

- Check whether the path width is large enough to move out the old tool.
- Check whether the old tool can serve a new fab's advanced technology products.

Step 1: Set product mixes and output targets with demand uncertainty

Different product mix and wafer output target plan will result in different equipment types and corresponding equipment quantities being eliminated. Since the demand uncertainty existed for a fab, Step 1 takes all possible output plans provided by the marketing department as the inputs, considering the product mix and output target variations. Each output plan needs to be reviewed through Step 2 to Step 5.

Step 2: Determine the maximal eliminable quantity of photolithography workstations

For reserving enough bottleneck capacity to fulfill the fab's monthly output target and product mix set in the previous step, Step 2 calculates the maximal eliminable quantity of photolithography machines. This step also helps Step 3 calculate the capacity requirements of non-bottleneck workstations based on output rate of bottleneck.

The formula of the maximal eliminable quantity is as follows:

$$M_{s,\text{photo}} = \max\left\{\left\lfloor q_{\text{photo}} - \frac{\text{RCAP}_{s,\text{photo}}}{\text{SCAP}_{s,\text{photo}}}\right\rfloor, 0\right\} \tag{1}$$

where $\frac{\text{RCAP}_{s,\text{photo}}}{\text{SCAP}_{s,\text{photo}}}$ is the required quantity of photolithography machines for fulfilling the monthly output target and corresponding product mix. The maximal eliminable quantity of photolithography workstations can be obtained by subtracting the required quantity from original quantity (q_{photo}). And this maximal eliminable quantity is just an initial solution because it needs to be reviewed further by Step 3 to Step 6.

Step 3: Reserve protective capacity on non-bottleneck workstation

Based on theory of constraint (TOC), non-bottleneck workstations should reserve some capacity to protect the system output under system uncertainties. Hence, the mechanism proposes that the output rate of non-photo workstation must be greater than that of photolithography workstations for reserving some protective capacity on non-bottleneck workstations. And the formula is

$$\frac{(q_i - M_{s,i}) \times \text{SCAP}_{s,i}}{\text{RCAP}_{s,i} \div \sum_{d=1}^{D} o_{s,d}} > \frac{(q_{\text{photo}} - M_{s,\text{photo}}) \times \text{SCAP}_{s,\text{photo}}}{\text{RCAP}_{s,\text{photo}} \div \sum_{d=1}^{D} o_{s,d}} \quad \text{for all } i \neq \text{photo} \tag{2}$$

where the numerators, $(q_{\text{photo}} - M_{s,\text{photo}}) \times \text{SCAP}_{s,\text{photo}}$ and $(q_i - M_{s,i}) \times \text{SCAP}_{s,i}$, represent available monthly capacity for photolithography workstation and non-photo workstation i after eliminating $M_{s,\text{photo}}$ and $M_{s,i}$ units, respectively. The denominators, $\text{RCAP}_{s,\text{photo}} \div \sum_{d=1}^{D} o_{s,d}$ and $\text{RCAP}_{s,i} \div \sum_{d=1}^{D} o_{s,d}$, represent the required weighted average process time per wafer piece for photolithography workstation and non-photo workstation i, respectively. $\frac{(q_i - M_{s,i}) \times \text{SCAP}_{s,i}}{\text{RCAP}_{s,i} \div \sum_{d=1}^{D} o_{s,d}}$ is the output rate of non-photo workstation. $\frac{(q_{\text{photo}} - M_{s,\text{photo}}) \times \text{SCAP}_{s,\text{photo}}}{\text{RCAP}_{s,\text{photo}} \div \sum_{d=1}^{D} o_{s,d}}$ is the output rate of photolithography workstations. The output rate is represented as number of wafer pieces per month.

For easy calculation on the eliminable candidates of each non-bottleneck workstations i, the Eq. (2) can be re-organized as the following equation.

$$M^*_{s,i} = \max\left\{\left\lfloor q_i - \frac{(q_{\text{photo}} - M_{s,\text{photo}}) \times \text{SCAP}_{s,\text{photo}} \times \text{RCAP}_{s,i}}{\text{RCAP}_{s,\text{photo}} \times \text{SCAP}_{s,i}}\right\rfloor, 0\right\} \quad \text{for all } i \neq \text{photo} \tag{3}$$

where $\frac{(q_{\text{photo}} - M_{s,\text{photo}}) \times \text{SCAP}_{s,\text{photo}} \times \text{RCAP}_{s,i}}{\text{RCAP}_{s,\text{photo}} \times \text{SCAP}_{s,i}}$ is the required quantity of non-bottleneck workstation i for reserving protective capacity. $M^*_{s,i}$ is the maximal tool quantity for workstation i which can be eliminated in output plan s.

Once, the quantity for elimination, $M^*_{s,i}$ is derived for every non-bottleneck workstation, go to Step 4.

Step 4: Estimate the impact on cycle time when eliminate each machine unit in workstation i

Shorter cycle time can improve cash flow, promote customer satisfaction, and reduce the risk of yield losses. Hence, the mechanism for tool portfolio elimination also needs to take cycle time into consideration. It also needs to identify the impact on production cycle time when one unit of specific equipment is eliminated.

Based on simulation data from SEMATCH for a 0.5 μm manufacturing line and the actual photolithography toolset data from two IBM Microelectronics manufacturing lines, Martin (1997) proposed a mathematical relationship between the cycle time and tool utilization, named X-factor theory. Kishimoto, Ozawa, Watanabe, and Martin (2001) used manufacturing simulator "ManSim" to evaluate the manufacturing performance and modified the basic X-factor equation as follows.

$$x_{s,i} = \frac{wc_{s,i}}{r_{s,i}} = \left(1 + \frac{(1-a_i)^{l_i}}{l_i+1} \times \frac{wm_i}{r_{s,i}} + \frac{(1-oa_i)^{oq_i}}{oq_i+1} \times \frac{om_i}{r_{s,i}}\right) \times \left(\frac{1-\frac{u_{s,i}}{2}}{1-u_{s,i}}\right) \tag{4}$$

$$x_{s,\mathrm{fab}} = \frac{\sum_{i=1}^{I} wc_{s,i}}{\sum_{i=1}^{I} r_{s,i}} \tag{5}$$

$$\boldsymbol{u_{s,i}} = \frac{\sum_{d=1}^{D}(o_{s,d} \times f_{d,i} \div t_{d,i} \div y_d)}{l_i \times a_i \times \mathrm{days/month}} \tag{6}$$

$$\boldsymbol{r_{s,i}} = \frac{\sum_{d=1}^{D}(o_{s,d} \times r_{d,i})}{\sum_{d=1} o_{s,d}} \tag{7}$$

where $x_{s,i}$ denotes the X-factor for workstation i in output plan s. $x_{s,\mathrm{fab}}$ denotes the overall fab line X-factor in output plan s. $wc_{s,i}$ denotes the cycle time of workstation i in output plan s. $r_{s,i}$ denotes the raw process time for workstation i in output plan s. wm_i denotes the mean length of the time periods that machines in workstation i are offline and unavailable, such as for repair, preventive maintenance, etc., l_i is the residual number of machines in workstation i available for specific processing sector. oa_i ($0 < \mathrm{value} < 1$) is the availability ratio that any one operator i at a certain period is able to process material. om_i denotes the mean length of the time periods that the operator is not available for product processing operations. om_i includes the situation where no operator is available because of breaks, oq_i is the total number of operators available for the specific workstation i. $u_{s,i}$ denotes the utilization rate of workstation i in output plan s.

Eq. (4) implies the following three meanings: (1) The utilization rate of a corresponding workstation will change when any machine is eliminated, because the equipment quantities will influence the utilization rate of the corresponding workstation. (2) The cycle time of each workstation will be changed whenever the utilization rate of each workstation is changed, because the raw process time of each workstation is assumed a constant value. (3) The cycle time of each workstation will have a significant increase when any machine with small equipment quantities, shorter process time, or low availability is eliminated.

Based on Eq. (4), the cycle time for workstation i can be estimated using:

$$wc_{s,i} = \left(1 + \frac{(1-a_i)^{l_i}}{l_i+1} \times \frac{wm_i}{r_{s,i}} + \frac{(1-oa_i)^{oq_i}}{oq_i+1} \times \frac{om_i}{r_{s,i}}\right) \times \left(\frac{1-\frac{u_{s,i}}{2}}{1-u_{s,i}}\right) \times r_{s,i} \tag{8}$$

When the jth equipment of workstation i is eliminated in output plan s, the cycle time increase, $\Delta wc_{s,i,j}$, is

$$\Delta wc_{s,i,j} = wc'_{s,i,j} - wc_{s,i,j} \tag{9}$$

where $wc'_{s,i,j}$ is the cycle time of workstation i after the jth equipment of workstation i is eliminated in output plan s. $wc_{s,i,j}$ is the cycle time of workstation i before the jth equipment of workstation i is eliminated in output plan s.

Since the maximal eliminable tool quantity for each workstation, $M^*_{s,i}$, was obtained in Step 3, the impact on cycle time for each jth eliminable machine unit of workstation i, $\Delta wc_{s,i,j}$, is easily derived by using the above formulation. When the calculation of impact on cycle time for each eliminable equipment unit of workstation i is completed in output plan s, the next step is to go for the final optimal solution.

Step 5: Determine the eliminable set for output plan s with maximum capital savings

As different equipment types and corresponding equipment quantities are eliminated from a fab, both the cycle time performance and the company-wide capital expenditure will be different. Hence, a sound tool elimination plan will win cost competitiveness in market and can maintain good cycle time performance. The Step 5 is to put these candidates that are bolted for elimination in the last step into the integer programming model to obtain the final optimal solution. From a company's financial point of view, the problem can be formulated as an integer program as follows:

A. Decision variables

$E_{s,i,j}$ the jth equipment of workstation i being eliminated in output plan s

B. Input parametric data

p_i capital expenditure for each machine in workstation i after deducting disassembly expenses
$r_{s,i}$ raw process time of workstation i in output plan s
x_s original X-factor in the donated fab in output plan s
x'_s upper-limit of X-factor in the donated fab in output plan s
$\Delta wc_{s,i,j}$ cycle time increase if the jth equipment unit of workstation i is eliminated in output plan s
$M_{s,i}$ the maximal tool quantity for workstation i which can be eliminated in output plan s

C. IP model

$$\text{Maximize} \quad \sum_{i=1}^{I}\sum_{j=1}^{M_{s,i}} E_{s,i,j} \times p_i \tag{10}$$

$$\text{Subject to} \quad \frac{ct'}{\sum_{i=1}^{I} r_{s,i}} \leqslant x'_s \tag{11}$$

$$ct' = x_s \times \sum_{i=1}^{I} r_{s,i} + \sum_{i=1}^{I}\sum_{j=1}^{M_{s,i}} E_{s,i,j} \times \Delta wc_{s,i,j} \tag{12}$$

$$E_{s,i,1} \geqslant E_{s,i,2} \geqslant \ldots \geqslant E_{s,i,M_{s,i}} \quad \text{for all } i \tag{13}$$

$$E_{s,i,j} = 1 \text{ or } 0 \quad \text{for all } i,j \tag{14}$$

In the above formulation, Eq. (10) is the objective function to measure the total capital expenditure savings on tool procurement which can be contributed to the requested fab. Based on the formulation of tool planning presented by Connors et al. (1996), Eq. (10) also implies that the donated fab's total equipment capital expenditure is minimized after elimination due to Max $\sum_{i=1}^{I}\sum_{j=1}^{M_{s,i}} E_{s,i,j} \times p_i = \text{Min}\sum_{i=1}^{I}(q_i - \sum_{j=1}^{M_{s,i}} E_{s,i,j}) \times p_i$.

Eq. (11) restricts the overall fab line's X-factor after eliminating tools from the donated fab to less than the upper-limit of X-factor.

Eq. (12) defines the overall fab line cycle time after eliminating tools is equal to the original overall fab line cycle time before tool elimination plus the total cycle time increases because of eliminated tools.

Eq. (13) ensures that equipment elimination occurs in sequence.

Eq. (14) restricts the decision variables to 0–1 variables. In addition, $E_{s,i,j} = 1$ if the $j$thequipment of workstation i is eliminated, $E_{s,i,j} = 0$ otherwise.

Based on the possible eliminate number of machines calculated by Step 0 to Step 3 and the impact on cycle time calculated by Step 4, the proposed IP model can derive the optimal tool elimination plan on the premise of satisfying X-factor limitation.

Step 6: Finalize eliminable tool list under all output plans

The final step repeatedly executes the above procedures from Step 2 to Step 5 for all output plans defined in Step 1. At the end of each repeat, the eliminable tool quantity of workstation i for each output plan s, $N_{s,i}$, is identified as the largest j value which makes the corresponding $E_{s,i,j}$ value be positive. And, $N_i^{\max}$, the final eliminable tool units of workstation i under all output plans is come out as the minimum of the eliminable number among all output plans, e.g., $N_i^{\max} = \text{Min}\{N_{1,i}, N_{2,i}, \cdots, N_{s,i}, \cdots, N_{S,i}\}$.

3. Application example

To demonstrate how the proposed mechanism can be used in practice and obtain an optimal set of eliminable tools, the actual data was collected from a leading wafer fabrication factory located in the Science-Based Industrial Park in Taiwan. The real case happened that transferring the equipments and products from the existing 8″ fabs in Taiwan to the new oversea 8″ fab in Mainland China. This factory strongly required help in solving the tool elimination issue due to the dramatic decreases in low-end technology demand at existing 8″ fab. At the same time, a new factory for producing low-end products is planned to setup in Mainland China, it seeks for any possible tool sources from this existing factory in order to reasonable deployment of assets among multi-sites. Thus, a comparison will be made between the proposed mechanism and the current approach used in this leading wafer fabrication factory, including eliminable quantity, capital saving, X-factor, etc.. The comparison results show that the fab production performance and the cost are much improved by the proposed mechanism.

In the application example, there are 83 kinds of workstations, in which 37 are batch workstations. The related tool information includes procurement price, tool quantity, availability, throughput, re-entry times, process time, etc. And the following example will state step-by-step how the proposed mechanism can be used in practice.

Based on the specific output plan showed in Table 2, Eq. (1) is applied to calculate the maximal eliminable quantity of photolithography workstation. The initial solution shows that there are 4 units of photolithography tools as candidates for tool elimination.

Subsequently, Eq. (3) is applied to reserve the enough protective capacity for non-bottleneck workstations. There are 71 machine units which are extracted from 53 workstations being selected as elimination candidates. The increases in cycle time were calculated individually when each of 71 tools was eliminated based on Eqs. (8) and (9).

In practice, the information related to candidates chosen for elimination is put into the integer programming model with cycle time performance and capital expenditure considerations. LINDO R6.01 was applied to solve the integer programming model. Considering output targets achievement, the final optimal solution shows that only 59 tools extracted from 46 workstations can be eliminated.

This leading wafer fabrication factory treats 85% utilization rate as the threshold for tool elimination without considering cycle time impact. That is, the equipment will be not eliminated if the workstation utilization reaches 85%. Detail of the practical tool elimination procedure can be found in Appendix A. Table 3 makes a comparison between the current industry's approach and the proposed mechanism in this paper. The results show that the company-wide capital expenditure and X-factor are much improved 17.19 M USD (18.2%) and 0.16 (7.6%) compared to the current industry's approach, respectively. The benefits are so significant because the proposed mechanism can effectively determine the right eliminable tools with large capital savings and little cycle time impact. Correspondingly, the current industry's approach eliminates the tools with cheap price and/or great impact, such as workstation 24, 25, 28, 29, 30, 32, 47, 64.

For further showing the benefits from the proposed mechanism, the more comparisons showed in Table 4 are made between the current industry's approach and the proposed mechanism. The 6 different scenarios of capacity scales, namely, 120%, 100%, 80%, 60%, 40%, and 20% of wafer output of the above application example, are included. The reason for such a setting is that 120% of wafer output is nearing upper-limit of tool capacity and 0% of wafer output is meaningless. The results in Fig. 2 and Table 5 show that the company-wide

Table 2
Monthly output plan and product mix (28 days/month, yield is assumed as 100%, $s = 1$)

Product	(1) Product 1/logic	(2) Product 2/memory	(3) Output = (1) + (2)
Wafer pieces	8150	8150	16,300

Table 3
A comparison for capital saving and X-factor (Upper-limit of X-factor = 2.00)

Eliminable tool	(1) Industry's approach	(2) Proposed mechanism	(3) Benefits = (2) − (1)
Quantity	60 U	59 U	–
Capital saving (M USD)	94.46	111.65	17.19 (Improve 18.2%)
X-factor	2.11	1.95	−0.16 (Improve 7.6%)

Table 4
Monthly output plan and product mix under variable capacity scales (28 days/month, yield is assumed as 100%)

Scenario	Capacity scale (%)	(1) Product 1	(2) Product 2	(3) Output = (1) + (2)
Case 1	120	9780	9780	19,560
Case 2	100	8150	8150	16,300
Case 3	80	6520	6520	13,040
Case 4	60	4890	4890	9780
Case 5	40	3260	3260	6520
Case 6	20	1630	1630	3260

Unit: Wafers/month.

capital expenditures are evidently improved 13.88 M USD (24.5%), 17.19 M USD (18.2%), 14.81 M USD (11.5%), 8.64 M USD (5.6%), 7.48 M USD (4.0%), and 7.48 M USD (3.6%) compared to the current industry's approach, respectively. And the results in Fig. 3 and Table 5 show that the X-factors are observably improved 0.43 (17.8%), 0.16 (7.6%), 0.29 (13.1%), 0.07 (4%), 0.08 (4.6%), and 0.03 (2.6%) compared to the current industry's approach, respectively. Hence, for each kind of different capacity scales, the proposed mechanism is showed to have larger capital savings and better X-factor performance.

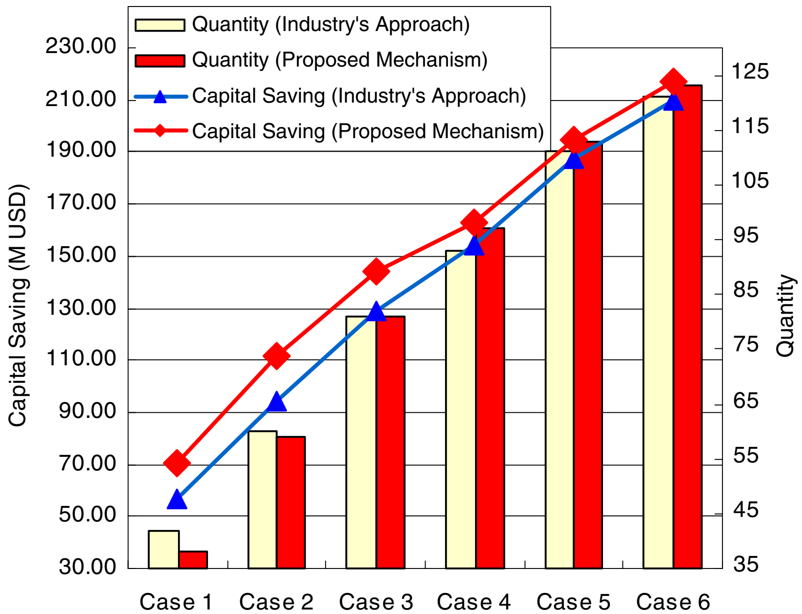
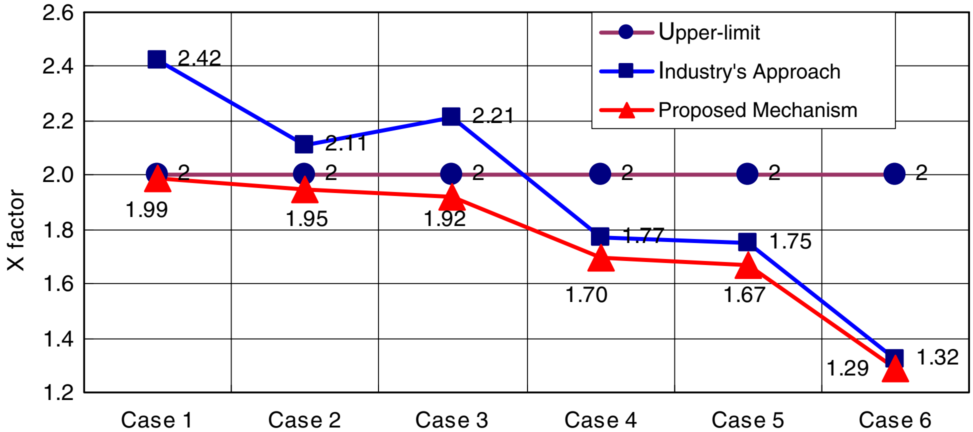


Fig. 2. Capital saving comparison.

Table 5
Performance comparison among different capacity scales (Upper-limit of X-factor = 2.00)

	Eliminable tool \Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Quantity	Industry's approach	42	60	81	93	111	121
	Proposed mechanism	38	59	81	97	113	123
Capital saving (M USD)	(a) Industry's approach	56.70	94.46	129.14	154.27	187.47	209.57
	(b) Proposed mechanism	70.58	111.65	143.95	162.91	194.95	217.05
	(c) Benefits = (b) − (a)	13.88	17.19	14.81	8.64	7.48	7.48
X-factor	(d) Industry's approach	2.420	2.110	2.210	1.770	1.750	1.324
	(e) Proposed mechanism	1.990	1.950	1.920	1.699	1.670	1.290
	(f) Improved rate = ((d) − (e))/(d)	17.8%	7.6%	13.1%	4%	4.6%	2.6%



Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Upper-limit	2	2	2	2	2	2
Industry's Approach	2.42	2.11	2.21	1.77	1.75	1.32
Proposed Mechanism	1.99	1.95	1.92	1.70	1.67	1.29

Fig. 3. X-factor comparison.

4. Conclusions

Both 200 and 300 mm wafer manufacturers must make decisions regarding tool elimination, due mainly to changes from demand, product mixes, and overseas fab capacity expansion. As different equipment types and corresponding equipment quantities are eliminated from a fab, different influences will result in both the fab production performance and the company-wide capital expenditure.

This paper proposed a mechanism for tool portfolio elimination that determines which equipment can be pruned, to provide sound information for management decision making. In the proposed mechanism, product mix, wafer output, capital expenditure, tool utilization, protective capacity, and cycle time are taken into consideration. An integer programming model was developed to eliminate trial-and-error in obtaining the optimal solution.

Compared to the current industry approach, the results show that the proposed mechanism can effectively determine the right eliminable tools with large capital savings and little cycle time impact. For future research, we can apply this method to solve midterm or short-term capacity planning, such as the tool shut-down planning for preventive maintenance. A decision support model to identify the trade-off between protective capacity reservation and capital savings may also be established.

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Appendix A. Practical tool elimination procedure

Step 1: Calculate the utilization rate of workstation i in output plan s.

$$\boldsymbol{u_i} = \frac{\sum_{d=1}^{D} o_{s,d} \times f_{d,i} \div t_{d,i} \div y_d}{q_i \times a_i \times \text{days/month}} \tag{15}$$

Step 2: Calculate the maximal tool quantity for workstation i which can be eliminated in output plan s.

This leading wafer fabrication factory treats 85% utilization rate as the threshold for tool elimination without considering cycle time impact. That is, the equipment will be not eliminated if the workstation utilization reaches 85%. And the maximal tool quantity for workstation i which can be eliminated in output plan s is

$$M_{s,i} = \max\left\{\left(q_i - \left\lceil\frac{q_i \times u_i}{0.85}\right\rceil\right), 0\right\}, \quad \text{if} \quad u_i < 85\% \tag{16}$$

$$M_{s,i} = 0, \quad \text{if} \quad u_i \geqslant 85\% \tag{17}$$

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