Computers & Industrial Engineering 59 (2010) 819–829

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Interim equipment shutdown planning for a wafer fab during economic downturns

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ARTICLE INFO

Article history:
Received 12 January 2010
Received in revised form 12 July 2010
Accepted 23 August 2010
Available online 26 August 2010

Keywords:
Tool portfolio
Cost reduction
Capacity planning
Semiconductor

ABSTRACT

Because of the low equipment utilization during periods of economic recession, managers of wafer fabs are forced to plan equipment shutdowns in order to reduce variable cost and reallocate resources. Unfortunately, few studies have proposed effective solutions for equipment shutdown planning in response to economic downturns. Taking into consideration the product mix, corresponding output target, excessive capacity, production performance impact and the variable cost savings, this paper presents a new mechanism for equipment shutdown planning using a developed integer programming model. The proposed mechanism effectively provides valuable recommendations for the managements of wafer fabs regarding the type and quantity of equipment to shut down.

1. Introduction

Due to low equipment utilization during periods of economic downturn, the managers of semiconductor firms must plan equipment shutdowns to drive down variable costs and make the related resource arrangement more efficient.

Equipment shutdown planning is one type of tool portfolio planning. Tool portfolio planning can generally be categorized as mid/long-term new tool planning for capacity expansion, mid/long-term tool elimination planning due to relocation to other plants or disposal and interim equipment shutdown planning due to economic recession. All of these categories aim towards the common goal of determining the type and quantity of equipment to add (or remove). The first and the second category will result in an increase (or decrease) in capital expenditure (or depreciation) while the third category affects the variable cost. The interim equipment shutdown planning results serve as a guideline for dispatching, operator relief planning in the manufacturing sector and financial planning. In practice, the interim equipment shutdown plan is subject to review and revision on a monthly basis.

Shutting down different equipment types and quantities has different impacts on output, production performance and cost reduction. From the cost reduction aspect, more could be saved in manufacturing expenses if more units of equipment are shut down. However, there is a need to keep specific varieties and quantities of equipment available to run operations smoothly, to meet the output target and to maintain high production performance. Therefore, semiconductor firm managers are compelled to develop a workable solution in an attempt to reconcile this conflict.

Equipment shutdown is an important topic for semiconductor firms requiring an efficient planning mechanism. With this motive, this paper proposes a sound mechanism for interim equipment shutdown planning based on determining the type and quantity of equipment suitable for shutdown.

Few studies have focused on proposing effective mechanisms for interim equipment shutdown to cope with economic recession. Previous studies have concentrated on new tool planning for capacity expansion (Bard, Srinivasan, & Tirupati, 1999; Bretthauer, 1996; Chen & Chen, 1996; Chou, 1999; Chou & Wu, 2002; Chou & You, 2001; Chung & Hsieh, 2004; Connors, Feigin, & Yao, 1996; Donohue, Hopp, & Spearman, 2002; Eppen, Martin, & Schrage, 1989; Grewal, Bruska, Wulfm, & Robinson, 1998; Hood, Bermon, & Barahona, 2003; Hsieh & Lin, 2002; Hua & Banerjee, 2000; Iwata, Taji, & Tamura, 2003; Mollaghsemi & Evans, 1994; Neacy et al., 1993; Swaminathan, 2000, 2002; Wang & Lin, 2002; Wu, Hsiung, & Hsu, 2005; Yang, 2000; Yoneda, Wada, & Haruki, 1992). Chung and Hsieh (2008) proposed a mechanism for mid/long-term equipment elimination for equipment relocation to overseas facilities.

Tool portfolio planning is a relatively complex and difficult problem. Common methodologies that are used to solve the tool portfolio planning problem in the literature include mathematics analytical method (for example, linear/integer programming and queuing network), simulation, heuristic algorithm, and combinations of the former ones. Linear/integer programming can determine the optimum tool portfolio if the considered factors can be formulated in the static model. Queuing network can rapidly

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doi:10.1016/j.cie.2010.08.009

derive performance estimates such as cycle time, work-in-process (WIP) and throughput. However, these estimates may be less accurate than those obtained by simulation (Wu et al., 2005). Mollaghsemi and Evans (1994) pointed out that the popularity of simulation is due to its flexibility and its ability to model systems when analytical methods have failed. In order to optimize a simulation model, it often must be used in conjunction with an optimum-seeking method. Heuristic algorithms can consider more important factors (for example, space and budget) under different manufacturing environments. Simulation and heuristic algorithms often require long calculation time because they must be repeated every time when a new tool is added (Neacy et al., 1993; Wu et al., 2005; Yoneda et al., 1992).

Bard et al. (1999) developed a heuristic algorithm to generate the candidate tools for new procurement and calculated the queuing time using the queuing theory to determine the tool portfolio that minimizes cycle time within a limited budget. For the capacity expansion in a semiconductor testing facility, Wang and Lin (2002) developed a heuristic algorithm and used a genetic algorithm to determine the type and quantity of the testers to be invested under the limited budget. Wu et al. (2005) developed a genetic algorithm embedded with a queuing analysis to solve the tool portfolio problem under cycle time constraints and demand uncertainty. It took about eight hours to complete the calculation.

Kishimoto, Ozawa, Watanabe, and Martin (2001) mentioned that customer demands for fast delivery of prototypes or mass-produced components are increasing because the life cycles of products are becoming shorter. Semiconductor manufacturers have been required to aim for "low cost" and "short time to market" to satisfy customer requirements and remain competitive in the marketplace. Thus, in considering the factors affecting tool portfolio planning, cycle time and cost are two critical factors that determine competitiveness in the semiconductor industry (Bard et al., 1999; Chen & Chen, 1996; Chou & Wu, 2002; Chou & You, 2001; Connors et al., 1996; Grewal et al., 1998; Iwata et al., 2003; Wu et al., 2005). Table 1 summarizes the tool portfolio planning literature. These papers are classified by cycle time, cost and the problem solving methodology.

Several studies have investigated cost reduction in the semiconductor industry (Carnes & Su, 1991; Dance, DiFloria, & Jimenez, 1996; Iwata & Wood, 2002; Nanez & Iturralde, 1995; Patel, Boswell, & Nelson, 1995; Rahaim, 1994), but these studies focused only on developing a wafer cost model without linking it to tool portfolio planning. Atwater and Chakravorty (1994), Blackstone and Cox (2002), Blackstone (2004), Craighead, Patterson, and Fredendall (2001), and Patterson, Fredendall, and Craighead (2002) mentioned that in the past, the literature rarely took excessive capacity and cost into consideration when studying tool portfolio planning. By considering product mix, corresponding output target, excessive capacity, production performance impact and the variable cost savings, this paper proposes an equipment shutdown planning mechanism. This mechanism will produce an effective and explicit recommendation for which type and what quantity of equipment to be shut down.

The rest of this paper is structured as follows. The following section presents an equipment shutdown planning mechanism. Section 3 presents an application example based on the actual data collected from a wafer fabrication factory situated in the Science-Based Industrial Park in Taiwan. Section 4 presents our conclusions.

2. Equipment shutdown planning mechanism

Before describing the mechanism, the notations used are listed and explained as follows.

2.1. Indexes

$I \equiv \{i \in \mathrm{N} : 1 \leqslant i \leqslant I\}$	Workstation type
$J \equiv \{j \in \mathrm{N} : 1 \leqslant j \leqslant J_i\}$	Machine number
$D \equiv \{d \in \mathrm{N} : 1 \leqslant d \leqslant D\}$	Product type
$K \equiv \{k \in \mathrm{N} : 1 \leqslant k \leqslant K_i\}$	Operator number

Table 1
Literature review about tool portfolio planning.

Methodology		Collocated methodology	Recent literature	Key factors considered	
				Cost	Cycle time
	Queuing network	Simulated annealing	Yoneda et al. (1992)	O	X
		Marginal allocation procedure	Connors, Feigin, and Yao (1996)	O	O
		Branch and bound algorithm	Bretthauer (1996)	O	X
		Qualitative reasoning	Chou (1999)	X	O
		Utility function	Chou and Wu (2002)	O	
Mathematics analytical method		Genetic algorithm	Wu et al. (2005)	O	
			Chou and You (2001)	O	O
	Linear/integer programming		Yang (2000)	X	X
			Hsieh and Lin (2002)	X	O
			Hua and Banerjee (2000)	O	X
	Stochastic integer programming		Eppen et al. (1989)	O	X
			Hood et al. (2003)	O	X
Simulation		STEP method	Mollaghsemi and Evans (1994)	X	O
		Response surface methodology	Chen and Chen (1996)	O	O
		Static capacity	Grewal et al. (1998)	O	O
Heuristic		Lagrangean relaxation, GB SB	Swaminathan (2000)	O	X
		Lagrangean relaxation, GB SB	Swaminathan (2002)	O	X
		Genetic algorithm	Wang and Lin (2002)	O	X
		BBCT	Chung and Hsieh (2004)	O	O
Combinations	Heuristic and queuing network	Simulated annealing	Bard et al. (1999)	O	O
			Donohue et al. (2002)	X	O
			Iwata et al. (2003)	O	O
	Heuristic and simulation		Neacy et al. (1993)	X	O
	Heuristic and integer programming		This paper	O	O

2.2. Capacity related parameters

a_{photo}, a_i	Tool availability for each machine unit at photolithography workstation and non-photolithography workstation i respectively
ar_{photo}, ar_i	Weighed average processing time for the production of each piece of wafer fab at photolithography workstation and non-photolithography workstation i respectively. $ar_i = \sum_{d=1}^{D}[(o_d f_{d,i})/(t_{d,i} y_d)]/\sum_{d=1}^{D} o_d$
$f_{d,i}$	Re-entry times of product d for workstation i
FC	Monthly wafer output target at photolithography workstation operating on the full-scale capacity
h	Working hours per month
M_{photo}, M_i	Upper-limit of equipment quantity at photolithography workstation and non-photolithography workstation i, respectively, for shutdown according to the given output plan
mt_{photo}, mt_i	Quantity of wafer product that one unit of equipment at each photolithography workstation and non-photolithography workstation i can produce on a monthly basis respectively
o_d	Output target for product d according to the given output plan. $d = 1, \ldots, D$
oa_k	Availability ratio denoting when any one operator k at a certain period is available for product processing operations
om_k	Mean time period that the operator k is not available for product processing operations
oq_i	Total number of operators available for the specific workstation i
q_{photo}, q_i	Original tool quantity for each photolithography workstation and non-photolithography workstation i respectively
QR_i	Minimum quantity of equipment at workstation i required for achieving the given output plan
qb_{photo}	Quantity of photolithography machines reserved for allowing a lower workstation utilization rate to reduce the shutdown effect on cycle time increase. $(0 \leqslant qb_{photo} \leqslant M_{photo})$
$t_{d,i}$	Throughput rate of product d on workstation i
$u_{i,j}$	Utilization rate of workstation i after the jth piece of equipment at workstation i is shut down. $u_{i,j} = \sum_{d=1}^{D}[(o_d f_{d,i})/(t_{d,i} y_d)]/[(q_i - j)a_i h]$
$wc_{i,j}$	Cycle time of workstation i before the jth piece of equipment at workstation i is shut down in the given output plan
wm_i	Mean time period in a day that machines in workstation i are unavailable for repair preventive maintenance, etc.
$\Delta wc_{photo,j}$, $\Delta wc_{i,j}$	Cycle time increases due to the shutdown of the jth piece of equipment at each photolithography workstation and non-photolithography workstation i, respectively
y_d	Yield rate of product d
$\left\lfloor \frac{x}{y} \right\rfloor$	The largest integer that is equal to or less than x divided by y
$\left\lceil \frac{x}{y} \right\rceil$	The smallest integer that is equal to or larger than x divided by y

2.3. Cost related parameters

$\Delta c_{photo,j}$, $\Delta c_{i,j}$	Variable cost savings for each photolithography workstation and non-photolithography workstation i respectively, if the jth piece of equipment is shut down
$CB_{i,j}$	Type II variable cost of workstation i when the jth piece of equipment at workstation i is shut down
$CF_{i,j}$	Type III variable cost of workstation i when the jth piece of equipment at workstation i is shut down
g	Variable cost reduction target percentage
TC	Original total variable cost of a fab
$v_{i,2}$	Average variable cost for rebooting each machine shut down at workstation i
$v_{i,3}$	Average variable cost for the hourly consumption of each machine at workstation i

2.4. Decision variables

$E_{photo,j}$, $E_{i,j}$	Indicate the jth piece of equipment shutdown at each photolithography workstation and non-photolithography workstation i. $E_{photo,j}$ (or $E_{i,j}$) = 1 if the jth piece of equipment at each photolithography workstation (or non-photolithography workstation i) is shut down, $E_{photo,j}$ (or $E_{i,j}$) = 0 otherwise.

2.4.1. Overall logic and framework

The equipment shutdown planning mechanism developed in this paper is designed to assist the semiconductor industry in effectively shutting down the appropriate type and quantity of equipment in an economic recession. When solving the equipment shutdown problem, the required product mix and output target must be satisfied, and the manufacturing cost savings, and the impact on production performance must be considered.

The proposed equipment shutdown planning mechanism includes four modules: (I) capacity check module; (II) cost saving estimation module; (III) cycle time effect assessment module; and (IV) equipment shutdown planning module. The overall flow of the mechanism is shown in Fig. 1 and explained as follows.

A typical semiconductor wafer fab includes several hundred pieces of equipment that are classified into many workstations. The products are loaded into the machines for processing by lots, with each production step conducted by a workstation. Each workstation usually consists of several identical equipments. The organization of workstation and equipment is shown in Fig. 2.

The photolithography tool is the most expensive piece of equipment in the foundry and has the highest number of repeated entries in the process and the longest procurement lead-time among all of the equipments. Previous studies (Yang, 2000, Shen and Leachman, 2003, Chung and Hsieh, 2008) on the equipment planning practice have identified the photolithography tool as the bottleneck equipment at the foundry. In this paper, photolithography tool is also views as the bottleneck.

The product mix and corresponding output target will influence the machine types and corresponding quantities required in the factory. Therefore, Module I calculates the maximum number of machines being shut down at each workstation based on the given output plan.

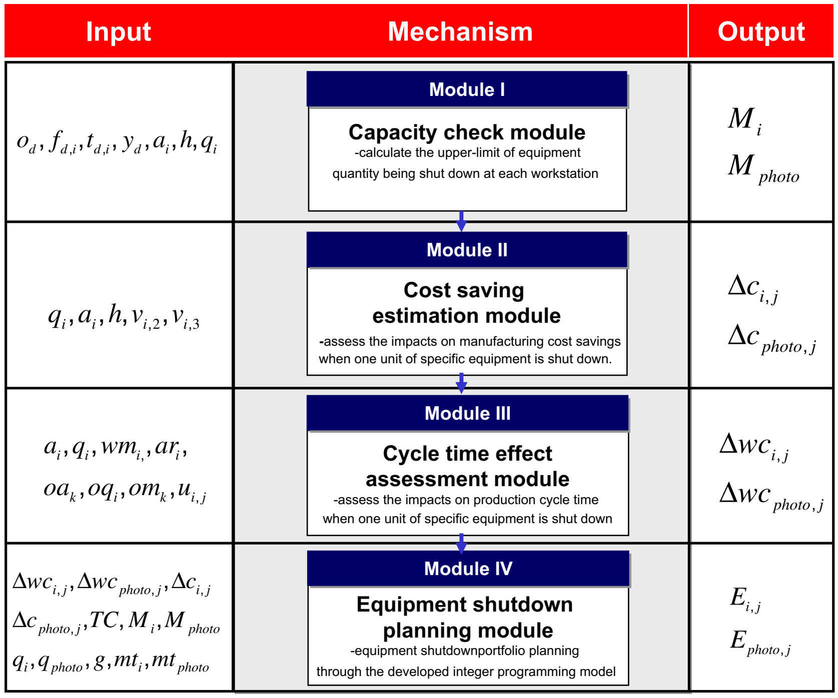

Fig. 1. Overall flow of equipment shutdown planning mechanism.

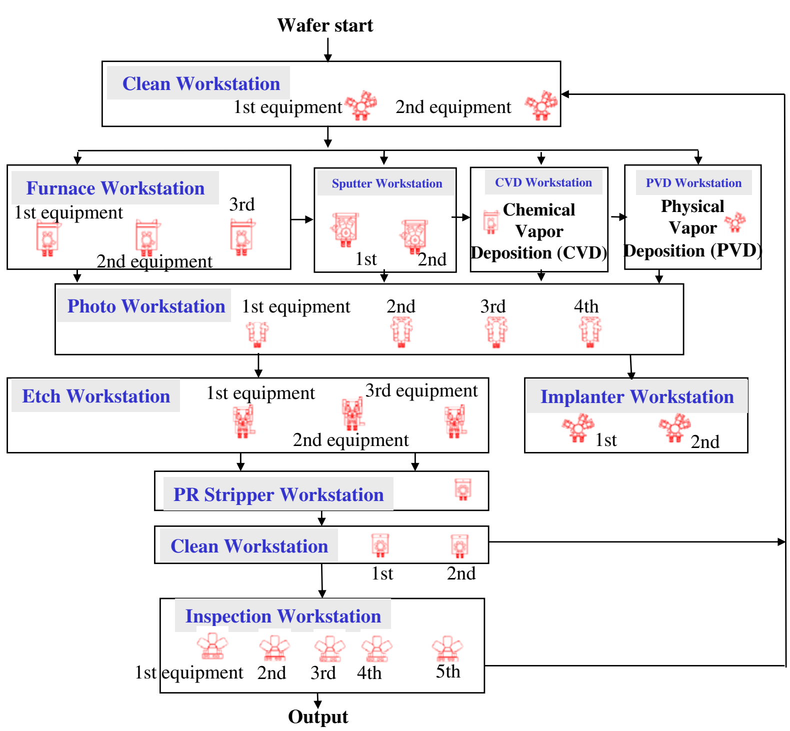

Fig. 2. Schematic representations of workstations and equipments.

Because the number of machine shutdowns will affect the operating cost, Module II assesses the impact on manufacturing cost savings when one unit of specific equipment is shut down.

When one equipment unit at a specific workstation is shut down, the utilization rate of other machines at this workstation increases. The increase in utilization rate prolongs the production cycle time. As different equipment types and corresponding quantities are shut down in a fab, the cycle time will be different. Module III identifies the impact on the production cycle time when one unit of specific equipment is shut down.

The purpose of Module IV is to determine the optimum equipment shutdown portfolio through the integer programming model. The proposed integer programming model, Module IV, effectively and explicitly recommends which type of equipment and what quantity to shut down to achieve the output plan, cost reduction targets, and a minimum cycle time impact.

2.5. Equipment shutdown planning mechanism

2.5.1. Capacity check module

The Module I calculates the upper-limit for the quantity of equipment to be shut down at each workstation based on the given output plan. Steps (1) and (2) consider the essential factors including the output target (o_d), re-entry times for each product type at every workstation ($f_{d,i}$), tool availability at each workstation (a_i), yield rate for each product type (y_d), and throughput rate at each workstation ($t_{d,i}$). This module adopts the same concept used by Chung and Hsieh (2008) but compresses the capacity formulas.

Step 1: Calculate QR_i, the minimum quantity of equipment required by workstation i according to the given output plan.

$$QR_i = \left\lceil \sum_{d=1}^{D} [(o_d f_{d,i})/(t_{d,i} y_d)]/(a_i h) \right\rceil \quad i = 1, \ldots, I \tag{1}$$

The numerator in Eq. (1) represents the required monthly processing time of workstation i to achieve the given output plan, and the denominator represents the monthly available capacity for each machine unit at workstation i.

Step 2: Calculate M_i, the upper-limit of equipment quantity possible for shutdown according to the given output plan.

$$M_i = \max\{(q_i - QR_i), 0\} \quad i = 1, \ldots, I \tag{2}$$

Eq. (2) subtracts the minimum equipment quantity required to achieve the given output plan (QR_i) from the quantity that the fab currently owns (q_i) to determine the upper-limit of equipment quantity to be shut down at each workstation (M_i).

2.5.2. Cost saving estimation module

The fab manufacturing cost may be subdivided into fixed cost and variable cost. Fixed cost includes the plant depreciation, machinery depreciation, direct and indirect labor, production support and related costs. The variable cost includes the cost of direct materials (for example, silicon chips) and some indirect materials. Carnes and Su (1991) suggested that variable cost includes the cost of consumables that are typically unique to each process tool. Utility or power usage, chemicals, gases, expendable parts and waste disposal costs are included in the cost of consumables.

A cost item related to whether or not a machine is shut down can be reflected by its corresponding activity drivers. Activity drivers are those factors that drive the cost of operational activities. (Hansen & Mowen, 2000). A variable cost item can be classified into three types according to the activity drivers: (1) Type I: the variable cost item uses wafer pieces as the activity driver and increases with the number of wafers processed (for example, raw wafers, control wafers, chemicals, gases, and containers). (2) Type II: the variable cost item uses equipment units as the activity driver and is used when any machine unit is shut down (for example, expendable parts for rebooting the machine). (3) Type III: the variable cost item uses time units as the activity driver and increases with the available time units for each operating machine (for example, utility, power supply, and waste disposal). The Types II and III variable costs are related to the amount of equipment shutdown.

When the machines that are shut down need to be turned on again, the Type II variable cost for rebooting j pieces of machines at workstation i, $CB_{i,j}$, is:

$$CB_{i,j} = j v_{i,2} \tag{3}$$

When the jth piece of equipment at workstation i is shut down, the Type III variable cost of workstation i, $CF_{i,j}$, is:

$$CF_{i,j} = (q_i - j) a_i h v_{i,3} \tag{4}$$

In Eq. (4): $(q_i - j)$ is the remaining quantity at workstation i after the jth piece of equipment at workstation i is shut down. $(q_i - j)a_i h$ represents the available monthly hours of workstation i to perform work.

Therefore, when the jth piece of equipment at workstation i is shut down, the variable cost that could be saved at workstation i, $\Delta c_{i,j}$ is

$$\Delta c_{i,j} = (CF_{i,j-1} + CB_{i,j-1}) - (CF_{i,j} + CB_{i,j}) = a_i h v_{i,3} - v_{i,2}, \quad \forall j \tag{5}$$

Eq. (5) shows that the variable cost of shutting down any of the j pieces of equipment at the workstation is equal.

2.5.3. Cycle time effect assessment module

The shorter the cycle time, the quicker the fab can respond to customer needs. Therefore, cycle time is one vital indicator of production performance considered in equipment shutdown planning. However, the utilization rate of other machines at this workstation increases after the equipment at a specific workstation is shut down. Such an increase in utilization rate prolongs the production cycle time, particularly for workstations with a smaller quantity of equipment.

To assess the impact on production cycle time when each piece of equipment is shut down, this module, as in Chung and Hsieh (2008), adopts the workstation cycle time estimation formula developed by Kishimoto et al. (2001). Thus, given an output target (o_d), the re-entry times for each product type at each workstation ($f_{d,i}$), the tool availability at each workstation (a_i), the yield rate for each product type (y_d), and the throughput of each workstation ($t_{d,i}$), the cycle time of workstation i, $wc_{i,j}$, when the jth piece of equipment at workstation i is shut down, is estimated as

$$\begin{aligned} wc_{i,j} = \{1 + [(1-a_i)^{(q_i-j)}/(q_i-j+1)(wm_i/ar_i) + (1-oa_k)^{oq_i}/ \\ (oq_i+1)(om_k/ar_i)]\}[1-(u_{i,j}/2)]/(1-u_{i,j})ar \end{aligned} \tag{6}$$

When the jth piece of equipment at workstation i is shut down, the cycle time increase, $\Delta wc_{i,j}$, is:

$$\Delta wc_{i,j} = wc_{i,j} - wc_{i,j-1} \tag{7}$$

2.5.4. Equipment shutdown planning module

Module IV targets equipment shutdown portfolio planning through the developed integer programming model. The model takes into considerations. (1) The upper-limit for the quantity being shutdown as derived in Module I for each workstation; (2) the shutdown effect of a specific equipment unit on the variable cost savings and on the cycle time according to the equipment type and total number of units already shut down; (3) the variable cost reduction target set by financial management; and (4) the establishment of protective capacity reserved at non-bottleneck workstations. The model formulation is shown below:

C. IP Model:

$$\text{minimize} \sum_{\substack{i=1 \\ i \neq photo}}^{I} \sum_{j=1}^{M_i} E_{i,j} \Delta wc_{i,j} + \sum_{j=1}^{M_{photo}} E_{photo,j} \Delta wc_{photo,j} \tag{8}$$

Subject to

$$\left[\left(\sum_{\substack{i=1 \\ iphoto}}^{I} \sum_{j=1}^{M_i} E_{i,j} \Delta c_{i,j} + \sum_{j=1}^{M_{photo}} E_{photo,j} \Delta c_{photo,j} \right) / TC \right] \geqslant g \tag{9}$$

$$\left(q_i - \sum_{j=1}^{M_i} E_{i,j} \right) mt_i \geqslant (q_{photo} - \sum_{j=1}^{M_{photo}} E_{photo,j}) mt_{photo} \quad \text{foralli} \neq photo \tag{10}$$

$$E_{i,j} \geqslant E_{i,j+1} \quad \forall i,j \in \{1,\ldots,M_i-1\} \tag{11}$$

$$E_{photo,j} \geqslant E_{photo,j+1} \quad j \in \{1,\ldots,M_{photo}-1\} \tag{12}$$

$$E_{i,j} \in \{0,1\} \quad \forall i,j \tag{13}$$

$$E_{photo,j} \in \{0,1\} \quad \forall j \tag{14}$$

Eq. (8) is the objective function used to measure the total cycle time impact on the entire fab after tool shutdown.

Eq. (9) requires that the variable cost reduction percentage after tool shutdown be greater than the variable cost cutting target ratio, g, to solve the corporate financial dilemma during an economic downturn.

The design concept of Eq. (10) is based on the theory of constraint (TOC) (Goldratt, 1990). That is, non-bottleneck workstations should reserve some capacity greater than the production needs to protect the system throughput and performance. The protective capacity of a non-bottleneck workstation is used to ensure that the production volume meets that of the photolithography workstation.

In Eq. (10), mt_{photo} and mt_i are the wafer quantities that one unit of equipment at the photolithography workstation and non-photolithography workstation i can produce on a monthly basis, respectively. The production quantity is derived from the following equations:

$$mt_{photo} = \frac{a_{photo}h}{ar_{photo}} \tag{15}$$

$$mt_i = \frac{a_i h}{ar_i} \tag{16}$$

Eqs. (11) and (12) ensure that equipment shutdown at a non-photolithography workstation i and at a photolithography workstation are performed in sequential serial number order. The design of Eqs. (11) and (12) ensures the correct result in calculating the shutdown effect of each additional unit, shown in Eq. (6). That is, the effect on the cycle time increase because the shutdown of the jth piece of equipment at workstation i can only be derived after shutting down $(j-1)$ equipment units of workstation i.

Eqs. (13) and (14) restrict the decision variables to 0–1 variables.

If there are many output plans under consideration, we can repeatedly execute Modules I–IV for each output plan and to determine the best type and quantity of equipment for shutdown according to each output plan. The number of shutdown equipment to be shut down at each workstation is determined as the minimal shutdown number among all output plans to ensure that each possible output plan can be accomplished.

3. Application example

This section contains four parts: Section 3.1 presents the actual data from company X, a well-known semiconductor plant in the Hsinchu Science-Based Industrial Park of Taiwan that will be used as a case study to demonstrate how the proposed mechanism is used in practice. Section 3.2 presents an analysis of the shutdown effect under variable output plans and cost reduction targets. Section 3.3 presents two practical methods used in company X and in another well-known semiconductor company Y as a benchmark for comparison to highlight the contribution of this paper to industrial practice. Finally, we present an analysis of the shutdown effect under variable bottleneck capacities and cost down targets.

3.1. Fundamental application

There are 83 kinds of workstations at company X, 37 of which are batch workstations. Some of company X's tool information is listed in Table 2, including tool quantity, availability at each workstation, throughput of each product type at each workstation, reentry times of each product type at each workstation, and variable cost savings.

The actual output plan provided by company X is 13, 040 wafers per month with 1:1 product mix, including logic product A ($o_1 = 6520$ wafers per month) and memory product B ($o_2 = 6520$ wafers per month). This wafer output plan is equivalent to 80% of company X's full-scale capacity. We implemented Eqs. (1) and (2) to identify 90 pieces of equipment available for shutdown. We then used Eqs. (3)–(7) to determine the shutdown effect of each piece of equipment at workstation i on variable cost savings and cycle time. Photolithography was identified as the bottleneck workstation. The goal was to reduce variable cost by 10%. This problem was solved by the branch and bound method using Lingo software to find the optimal solution of this problem. Experiments were carried out on a PC with a 2.66 Intel Core i5-750 CPU*4. The required CPU time was around 5–10 s per run for 90 variables and 271 constraints. The final optimal solution showed that 19 units of equipment should be shut down, and the cycle time increased by 0.58% (42.3 min).

3.2. Shutdown effect under variable output plans

To illustrate the equipment shutdown decision problem according to different output plans, three scenarios are proposed, as

Table 2
Part of company X's tool information.

Workstation	q_i	a_i	$t_{1,i}$ (pcs/day)	$t_{2,i}$ (pcs/day)	$f_{1,i}$	$f_{2,i}$	w_{mi} (min)	$\Delta c_{i,j}$ (USD K)	Batch size
w01	2	0.97	12,000	12,500	17	21	0.133	700	1
w02	3	0.97	12,000	12,500	26	30	0.133	700	1
w03	1	1.00	35,928	72,000	1	1	0.000	529	1
w04	1	1.00	12,000	12,000	3	3	0.000	975	1
w05	1	1.00	1500	1500	1	1	0.000	400	1
w06	1	1.00	35,928	72,000	1	1	0.000	400	1
w07	7	0.97	2250	2250	12	20	0.150	660	2
w08	3	0.97	2667	2625	6	3	0.150	660	2
w09	3	0.98	562	563	1	3	0.067	400	1
w10	1	0.98	–	750	0	1	0.100	400	1
w11	2	0.98	621	625	1	1	0.100	300	1
wl2	5	0.96	400	400	2	2	0.200	900	1
w81	1	1.00	3429	3450	1	1	0.000	200	2
w82	4	1.00	500	500	1	1	0.000	390	1
w83	1	1.00	12,000	12,000	1	1	0.00	390	1

Table 3
Monthly output plan and product mix under variable capacity scales (28 days/month, yield is assumed as 100%).

Output plan	(1) Product 1, o_1	(2) Product 2, o_2	(3) Output = (1)+(2)
I	6520	6520	13,040
II	4890	4890	9780
III	3260	3260	6520

Unit: Wafers/month.

shown in Table 3. Output plans I, II, and III are to operate at 80%, 60%, and 40% of full-scale capacity, respectively, each with the same product mix (1:1). Five cost reduction targets, namely 5%, 10%, 15%, 20%, 25%, were applied in the analysis of the shutdown impact on production performance. Fig. 3 presents the following facts.

In each output plan, if the cost reduction percentage increases, the cycle time will increase. For example, in output plan I in Fig. 3, when the cost reduction target increases from 10% to 25%, more equipment is removed and the cycle time increases from 0.58% to 6.80%. The results show that such an analysis could effectively indicate the trade-off relationship between cycle time increases and cost savings for equipment shutdown planning.

3.3. Comparison with current industrial practices

Comparing the performance of the proposed mechanism with that of the industry approach, two current practices at companies X and Y were investigated to analyze the equipment shutdown impacts on cycle time and cost savings in this section.

Company X uses the output drop-off percentage to determine the shutdown quantity for each workstation. The formula for calculating the shutdown quantity at each photolithography and non-photolithography workstation i is,

$$M_i = \left\lceil q_i - q_i\left(\sum_{d=1}^{D} o_d/FC\right)\right\rceil \quad i = 1,\ldots,I \tag{17}$$

where $q_i\left(\sum_{d=1}^{D} o_d/FC\right)$ is the minimum quantity of equipment required for achieving the given output plan.

To maintain a high utilization rate for each workstation, company Y considers an 85% utilization rate as the threshold for making shutdown decisions. That is, no equipment will be shutdown if the workstation utilization rate is greater than 85%. The equations for calculating the shutdown quantity at each photolithography and non-photolithography workstation i is (Chung and Hsieh, 2008),

$$M_i = \max\{(q_i - \lceil q_i u_i/0.85\rceil), 0\}, \quad \text{if } u_i < 0.85 \tag{18}$$

$$M_i = 0, \quad \text{if } u_i \geqslant 0.85$$

$$\text{where } u_{i,j} = \sum_{d=1}^{D}[(o_d f_{d,i})/(t_{d,i} y_d)]/[(q_i - j)a_i h]$$

To show the equipment shutdown effects on cycle time and on cost savings, we derived the results for output plans I–III by first adopting the approaches used at companies X and Y. Based on the cost savings achieved by companies X and Y, we ran the proposed mechanism for each individual case. The corresponding results, shown in Table 4, led us to the following conclusions.

1. With the same level of cost savings, the mechanism proposed in this paper will result in a lower cycle time impact than the current practice of company X. For example, for output plan II, Table 3 shows that company X has a cost saving of 10.77%, but the cycle time increase is as high as 13.65%. However, with the same cost saving target achieved by companies X ($g\%$ = 10.77%), the mechanism we propose has a cycle time impact of only 0.39%.
2. Compared to company Y's approach, the results also show that the proposed mechanism has a lower cycle time impact using the same cost saving target. Company Y treats an 85% workstation utilization rate as the threshold for tool shutdown. This rate will result in an extreme increase in cycle time: 71.32%, 50%, and 57.68% for output plans I, II, and III with the cost saving at 39.4%, 45.04%, and 53.72%, respectively. However, by using the same cost saving target achieved by companies Y, the mechanism we propose would result in lower cycle time impacts of 53.06%, 35.54%, and 39.88% for output plans I, II, and III, respectively.

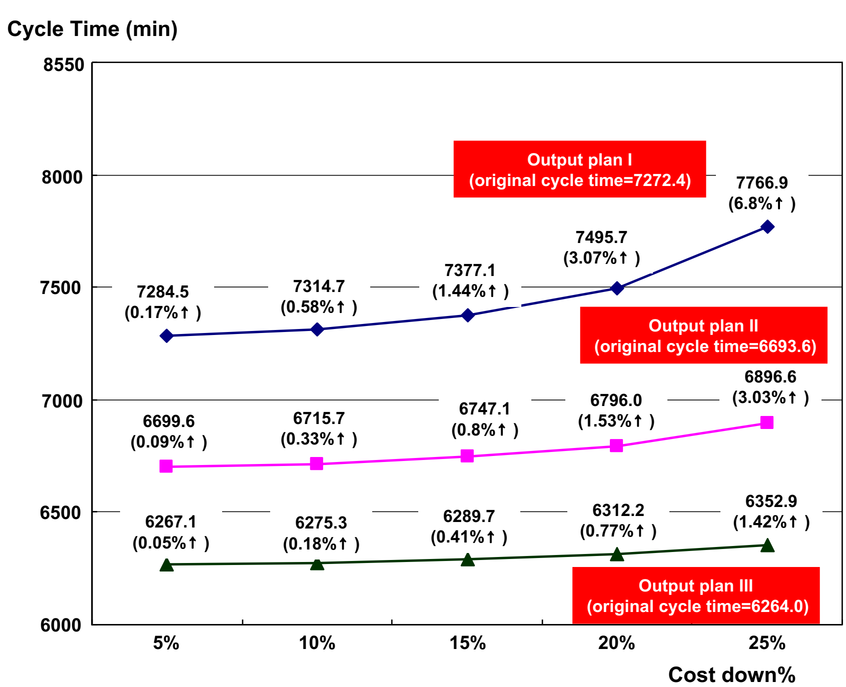

Fig. 3. Shutdown effect on cycle time under different output plans.

Table 4
Equipment shutdown effect with industry's approaches.

Output plan		Company X	Proposed mechanism	Company Y	Proposed mechanism
I	Cycle time increase rate	4.16%	0.18%	71.32%	53.06%
	(Cycle time after equipments shutdown)	(7603.1)	(7285.3)	(12505.2)	(11131.1)
	Cost saving rate	5.38%		39.40%	
	(Saving amount)	(205)		(1503)	
II	Cycle time increase rate	13.65%	0.39%	50%	35.54%
	(Cycle time after equipments shutdown)	(7588.4)	(6719.5)	(10015.5)	(9072.5)
	Cost saving rate	10.77%		45.04%	
	(Saving amount)	(411)		(1718)	
III	Cycle time increase rate	25.36%	0.48%	57.68%	39.88%
	(Cycle time after equipments shutdown)	(9150.5)	(6293.7)	(11509.7)	(8762.1)
	Cost saving rate	16.15%		53.72%	
	(Saving amount)	(616)		(2049)	

Remark: original total variable cost is USD 3814.7 K/month.

3. The study results demonstrate the superiority of the proposed mechanism and the value of this paper in industrial applications.

3.4. Shutdown effect under variable bottleneck capacities

In this section, to assess the cycle time increases based on different shutdown photolithography machines quantities, we enforced the number of shutdown to a specific value that is between the upper-limit of shutdown quantity (M_{photo}) and 0. Thus, we designedly added a constraint, Eq. (19), into our integer programming model and treated qb_{photo} as a parameter:

$$\sum_{j=1}^{M_{photo}} E_{photo,j} = M_{photo} - qb_{photo} \tag{19}$$

where qb_{photo} is the quantity of photolithography machines reserved to allow a lower workstation utilization rate to reduce the shutdown effect on cycle time increase.

From the results shown in Figs. 4–6 and Table 5, we can see the following.

1. For each qb_{photo} in output plan I, II, and III, we can find: the more the reduction target increases, the more the cycle time increases.
2. The shutdown quantity of photolithography machines is a critical factor that influences the cycle time. For example, in Fig. 4, when qb_{photo} increases from 0 to 1, 2 units (i.e., $\sum_{j=1}^{M_{photo}} E_{photo,j}$ decreases from 6 to 5, 4) with the cost reduction target set at 25% for output plan I, the cycle time increase rate will drop from 14.19% to 6.95%, and 6.8% respectively because the shutdown quantity of photolithography tools is decreased. The same situation can be found in Fig. 6, when qb_{photo} increases from 0 to 1, 2, 3 units (i.e., $\sum_{j=1}^{M_{photo}} E_{photo,j}$ decreases from 9 to 8, 7, 6) with the cost reduction target set at 25% for output plan III, the cycle time increase rate will drop from 2.34% to 1.56%, 1.44% and 1.42%.
3. Under the pre-established cost reduction target, if the shutdown quantity of photolithography tools is greatly decreased, many more additional units of non-photolithography tools must be shut down to compensate for the cost savings. Meanwhile, the cycle time tends to move upwards. For example, in Fig. 4, when qb_{photo} increases to 3 and 4 with the cost reduction

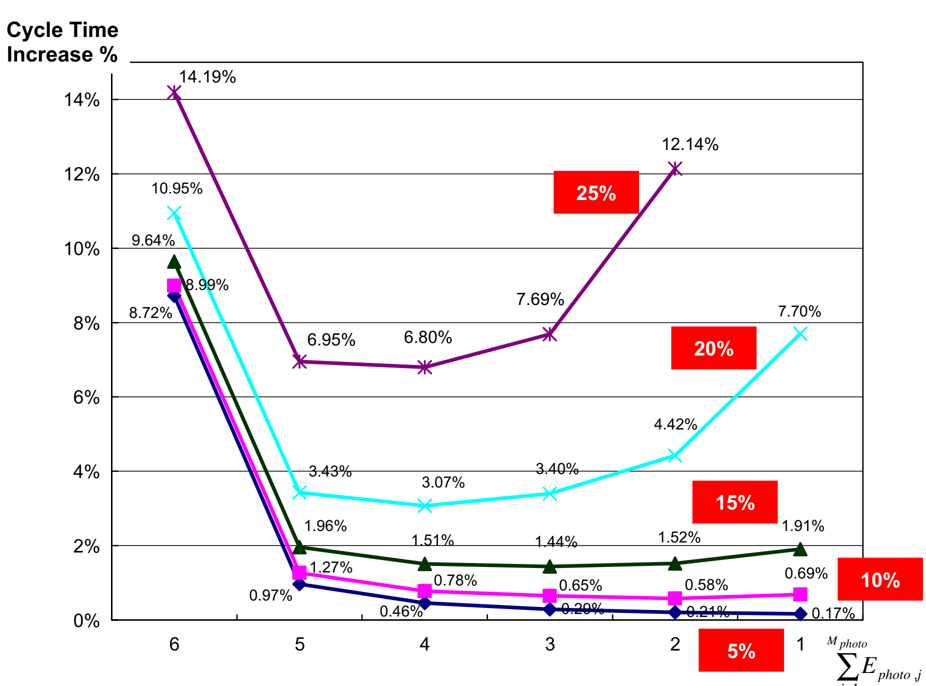

Fig. 4. Shutdown effect on cycle time increase in output plan I.

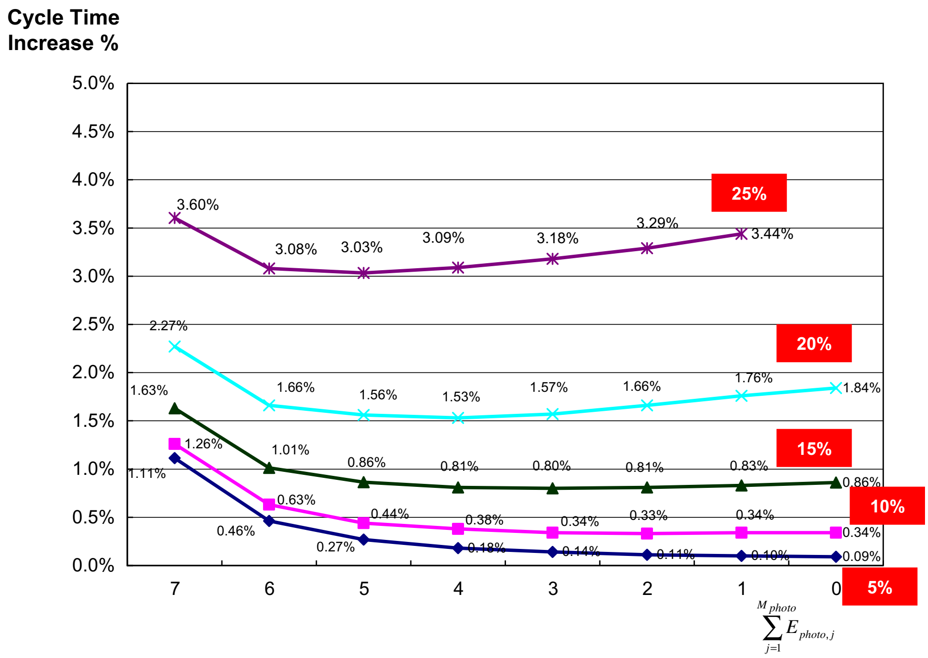

Fig. 5. Shutdown effect on cycle time increase in output plan II.

target set at 25% for output plan I, the cycle time increase rate moves up, which is 7.69% and 12.14%, respectively. In Fig. 5, when qb_{photo} increases to 3, 4, 5 and 6 (i.e. $\sum E_{photo,j} = 4, 3, 2$ and 1) with the cost reduction target set at 25% for output plan II, the cycle time increase rate moves up, which is 3.09%, 3.18%, 3.29% and 3.44%, respectively. This move-up results imply that to achieve the pre-established cost reduction target, more non-photolithography tools should be shut down to offset the cost effect of a lower shutdown quantity of photolithography tools. The additional units of non-photolithography tools being shut down are more influential on cycle time than the decreased number of photolithography tools being shut down. Finally, when qb_{photo} increases to 5 or 6 in output plan I in Fig. 4 (or when qb_{photo} increases to 7 in output plan II in Fig. 5), the non-bottleneck tools do not have enough capacity to satisfy Eq. (10) such that there is no feasible solution for the entire integer programming model.

4. The cycle time increase rate drops significantly when qb_{photo} is equal to 1. (i.e. $\sum_{j=1}^{M_{photo}} E_{photo,j}$ decreases from 6 to 5 in Fig. 4, from 7 to 6 in Fig. 5, and from 9 to 8 in Fig. 6). Besides, comparing with Figs. 5 and 6, the cycle time drop-off rate in Fig. 4 is the most significant when qb_{photo} is equal to 1. That is, reserving one unit of photolithography tool could lead to a good cycle time performance. The results are summarized in Table 5.
5. The above experiments show that an appropriate combination of machine quantities at bottleneck and non-bottleneck workstations will help to substantially compress cycle time.

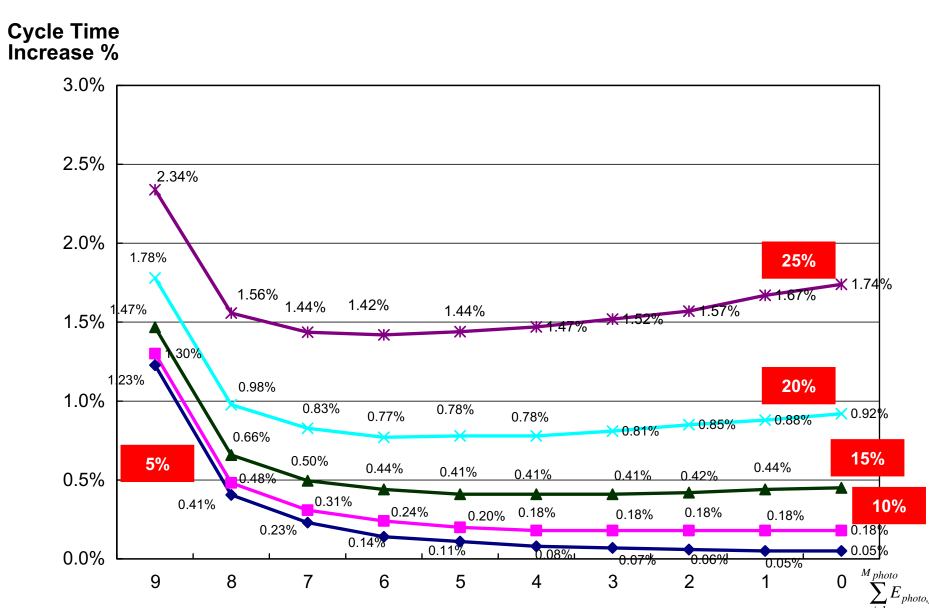

Fig. 6. Shutdown effect on cycle time increase in output plan III.

Table 5
Shutdown effect on cycle time under variable bottleneck capacity.

Output Plan	Original cycle time	M_{photo}	$q_{b\ \text{photo}}$	$\sum_{i=1}^{M_{photo}} E_{photo}$	Photo utilization	Cost down target				
						5%	10%	15%	20%	25%
I	(7272.4)	6	0	6	97.9%	8.72% (7906.6)	8.99% (7926.2)	9.64% (7973.5)	10.95% (8068.7)	14.19% (8304.4)
			1	5	85.7%	0.97% (7342.6)	1.27% (7364.8)	1.96% (7414.9)	3.43% (7521.9)	6.95% (7777.8)
			2	4	76.2%	0.46% (7305.6)	0.78% (7329.1)	1.51% (7382.2)	3.07% (7495.7)	6.80% (7766.9)
			3	3	68.6%	0.29% (7293.2)	0.65% (7319.5)	1.44% (7377.1)	3.40% (7519.7)	7.69% (7831.7)
			4	2	62.3%	0.21% (7287.3)	0.58% (7314.7)	1.52% (7382.9)	4.42% (7593.8)	12.14% (8155.3)
			5	1	57.1%	0.17% (7284.5)	0.69% (7322.3)	1.91% (7411.3)	7.70% (7832.4)	– –
			6	0	52.7%	– –	– –	– –	– –	– –
II	(6693.6)	7	0	7	85.7%	1.11% (6768.2)	1.26% (6777.9)	1.63% (6802.7)	2.27% (6845.5)	3.60% (6934.9)
			1	6	73.4%	0.46% (6724.6)	0.63% (6735.9)	1.01% (6761.4)	1.66% (6804.7)	3.08% (6899.7)
			2	5	64.3%	0.27% (6711.5)	0.44% (6723.0)	0.86% (6751.5)	1.56% (6798.0)	3.03% (6896.6)
			3	4	57.1%	0.18% (6705.6)	0.38% (6719.0)	0.81% (6747.8)	1.53% (6796.0)	3.09% (6900.4)
			4	3	51.4%	0.14% (6702.9)	0.34% (6716.3)	0.80% (6747.1)	1.57% (6798.7)	3.18% (6906.4)
			5	2	46.7%	0.11% (6700.9)	0.33% (6715.7)	0.81% (6747.8)	1.66% (6804.7)	3.29% (6913.8)
			6	1	42.8%	0.10% (6700.3)	0.34% (6716.3)	0.83% (6749.1)	1.76% (6811.4)	3.44% (6923.8)
			7	0	39.5%	0.09% (6699.6)	0.34% (6716.3)	0.86% (6751.1)	1.84% (6816.7)	–
III	(6264.0)	9	0	9	85.8%	1.23% (6340.9)	1.30% (6345.5)	1.47% (6355.9)	1.78% (6375.5)	2.34% (6410.6)
			1	8	68.6%	0.41% (6289.4)	0.48% (6294.1)	0.66% (6305.2)	0.98% (6325.2)	1.56% (6361.6)
			2	7	57.2%	0.23% (6278.4)	0.31% (6283.4)	0.50% (6295.0)	0.83% (6315.8)	1.44% (6354.0)
			3	6	49.0%	0.14% (6272.8)	0.24% (6279.0)	0.44% (6291.5)	0.77% (6312.2)	1.42% (6352.9)
			4	5	42.9%	0.11% (6270.9)	0.20% (6276.5)	0.41% (6289.7)	0.78% (6312.8)	1.44% (6354.2)
			5	4	38.1%	0.08% (6269.0)	0.18% (6275.3)	0.41% (6289.7)	0.78% (6312.8)	1.47% (6356.1)
			6	3	34.3%	0.07% (6268.4)	0.18% (6275.3)	0.41% (6289.7)	0.81% (6314.7)	1.52% (6359.2)
			7	2	31.2%	0.06% (6267.7)	0.18% (6275.3)	0.42% (6290.3)	0.85% (6317.2)	1.57% (6362.3)
			8	1	28.6%	0.05% (6267.1)	0.18% (6275.3)	0.44% (6291.5)	0.88% (6319.1)	1.67% (6368.6)
			9	0	26.4%	0.05% (6267.1)	0.18% (6275.3)	0.45% (6292.2)	0.92% (6321.6)	1.74% (6373.0)

Remark Cycle time increase rate=(Cycle time after equipments shutdown-original cycle time)/original cycle time

x.xx% → Cycle time increase rate
(xxxx.x) → Cycle time after equipments shutdown (unit: min)
- / - → Infeasible solution

4. Conclusion

To enhance operating performance during a period of economic downturn, managers of semiconductor firms engage in strategic equipment shutdown planning to drive cost reduction and adjust the allocation of resources. Building a sound mechanism to determine the type and quantity of equipment suitable for shutdown is very important.

This paper proposed an equipment shutdown planning mechanism and developed an integer programming model to assist firms in effectively mapping out the optimum portfolio for equipment shutdown. Factors including product mix, corresponding output targets, protective capacity and the variable cost reduction targets were taken into consideration. The objective of the proposed integer programming model is to minimize the effect of shutdown on cycle time to maintain the time-to-market competitiveness during an economic recession. Compared with two current industry practices, the portfolio derived by our proposed mechanism has a smaller cycle time impact while achieving the threshold cost savings.

The experimental results show that the equipment shutdown planning mechanism proposed in this paper is an excellent tool for analyzing the trade-off relationship between cycle time increases and cost savings. We also determined that appropriately decreasing bottleneck machine utilization and reserving some protective capacity for non-bottleneck machines help to hold down the cycle time increase rate during the shutdown.

The managerial implications are concluded as follows.

1. The shutdown quantity of photolithography machines is a critical factor that influences the cycle time. An appropriate combination of machine quantities at bottleneck and non-bottleneck workstations will help to substantially compress cycle time.
2. Reserving insufficient or too many units of photolithography tools could result in poor cycle time performance when planning equipment shutdown. The proposed mechanism can effectively provide a valuable analysis tool and trade-off information for management decision-making.
3. For future research, the problems related to mid-term or short-term capacity adjustment, such as inter-fab backup of equipment for meeting monthly capacity requirements, the timing of equipment disposal, and application in other industry, can be studied.

Acknowledgements

The authors graciously acknowledge the great supports of Frank Kao (human resources director), Charles Hung (production planning director), Chen-Fu Chien (IE deputy director), and Tom Wu (capacity planning manager) of the Taiwan Semiconductor Manufacturing Company.

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