Int J Adv Manuf Technol (2006) 30: 727–737
DOI 10.1007/s00170-005-0105-y

ORIGINAL ARTICLE

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Production-flow-value-based job dispatching method for semiconductor manufacturing

Received: 25 January 2005 / Accepted: 2 June 2005 / Published online: 17 November 2005

Abstract In a wafer manufacturing system, the value added to a particular product at a station may differ significantly from that added to a different product at the same station. If an enterprise concentrates mainly on generating profits, throughput becomes a poor performance measurement for a manufacturing system. Job dispatching rules based on maximum throughput no longer guarantee maximizing profit. Hence, profitability would be a good alternative measurement. The main purpose of this study is to develop a production-flow-value-based job dispatching rule (PFV) by the theory of constraints (TOC) for wafer fabrication. This study derives a TOC cost estimation method and a profitability estimate of a WIP-wafer lot. Jobs are then prioritized based on their profitability. Thus the PFV job dispatching rule is developed. For comparison, two job dispatching rules, MCR and MBS, are also arbitrarily selected to perform simulations. The simulation results reveal that the proposed PFV maximizes the production flow value, while MCR and MBS do not.

Keywords Dispatching rules · Production flow value · System resource time · Theory of constraints

1 Introduction

Several characteristics of wafer fabrication make it challenging: complex product flows, random yields, diverse equipment characteristics, unpredictable equipment downtime, production and development using shared facilities, and time-consuming and difficult data acquisition and maintenance. Hence various researchers have devoted themselves to developing dispatching rules [1–4]. Many traditional dispatching rules are applied to wafer fabrications. These rules focus mainly on increasing productivity, and use throughput as a measurement. However, in wafer manufacturing systems, the value added by an operation for a product at a station may vary considerably between different products even at the same station. If an enterprise, focuses mainly on generating profit, throughput stops being a good measurement. Job dispatching rules based on maximum throughput no longer guarantee profit maximization. Consequently, the job profitability provides a good alternative measurement.

The goal of a business is "to make money in the present and in the future", and thus business performance is measured by net profit and return on investment. Therefore, to maximize the profit in a semiconductor plant, the dispatching algorithm should be adjusted to maximize the production flow value per time unit. Pierce and Yurtsever [5] presented a value-based dispatching concept for profit maximization.

Maximizing the production flow value requires a reasonable method of estimating work-in-process (WIP) inventory cost. The activity-based costing (ABC) [6–9] largely focuses on establishing a product cost for broadening the scope of activities for which the cost can be causally linked to products. ABC does provide a reasonable method of product costing, and cannot achieve anything in maximizing system profit. For example, a powerful but expensive machine is much more effective than an old but cheap machine. Production can be performed using either machine. However, based on ABC costing, the cost of the product produced using the powerful machine would be much higher than that produced using the cheap machine. This cost differential prevents jobs from being performed using expensive machines. Consequently, the product yield rate is poor and the system productivity is not fully utilized.

The theory of constraints (TOC), developed primarily by Eli Goldratt [10], asserts that constraints determine system

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performance, and a production system can be improved by relaxing the constraints. A constraint in a production system is usually a bottleneck station or machine. However, so far, TOC is mostly applied to the production plan [11–14], and TOC costing is seldom discussed. If a product's cost is based on the usage of the bottleneck machine, the job dispatching people would try to avoiding assigning jobs to bottleneck machines. Provided it is not a bottleneck machine, a powerful but expensive machine would never lead to high cost product. In this case, manufacturing people would strive to improve the productivity of the bottleneck machine group. After improving the productivity of the old bottleneck machine group, a new bottleneck machine group would develop and they would continue improving until the productivity of the production machines is balanced. At this point the production system is optimized. Notably, the TOC costing eventually would become very close to that of the ABC. The costing method affects job dispatches, and also manufacturing strategies. Hence, a TOC costing should be developed before developing a value-based job dispatching rule.

This study develops a production-flow-value-based job dispatching rule by a TOC costing for wafer fabrication. This study derives a TOC cost estimation method for a WIP wafer. The current profitability of a WIP wafer can be estimated assuming that the current market price of a product is known. The production cost and value addition of each operation for a specific job can be estimated based on the developed product costing. For single-wafer-lot jobs or batch jobs, jobs are prioritized according to the descending order of the production flow value per time unit. This approach is used to develop a production-flow-value-based job dispatching rule (PFV).

This study comprises two major parts. Besides the development of the PFV job dispatching rule, numerous different simulations are performed for evaluation purposes. A wafer fabrication simulation model is built using a commercial simulation tool, eM-Plant, and, two are dispatching rules besides PFV, MCR and MBS are arbitrarily chosen in a series simulation. Several measurements for example production cycle times, the average WIP inventory cost, system resources time consumption, system resources time unit profitability, etc. are used to evaluate PFV performance.

2 Review of past research on job dispatching

In practice, the most common approach to shop-floor control problems has been the use of dispatching rules. Such rules are surveyed in Baker [15], Blackstone et al. [1] and Panwalkar and Iskander [2]. Most commercially available computer-aided manufacturing (CAM) systems for semiconductor manufacturing make use of this approach. Baudin [16] listed five dispatching rules: (1) first in first out (FIFO), (2) earliest due date (EDD), (3) shortest processing time(SPT), (4) least slack (LS), and (5) critical ratio (CR). Moreover, Glassey and Resende [17] develop a dispatching rule to complement the starvation avoidance input regulation policy. This rule aims to minimize the average queue in front of the bottleneck by prioritizing lots that are expected to encounter a shorter queue at their next visit. Lozinski and Glassey [18] present a graphical tool to implement the starvation avoidance policy. A drawback of the starvation avoidance approach is the assumption of a fixed bottleneck with a location that is known prior. Pierce and Yurtsever [5] propose a value-based dispatching concept that suggests additional objectives such as profit maximization, market share growth and technology development along with achieving manufacturing goals.

An interesting class of scheduling problems that emerges in semiconductor manufacturing is that of scheduling batch processing machines. Ikura and Gimple [19] presented algorithms to decide whether a feasible schedule exists for the situation involving agreeable release times and due dates. If feasible schedules exist, their algorithm will minimize the completion time. A general rule, termed the minimum batch size rule (MBS) by Glassey and Weng [20], states that the server starts service only when the queue contains a minimum number of unit a, is used for bulk service systems. The MBS does not take advantage of forecast if some future information is available. Therefore, Glassey and Weng [20] presented a “dynamic batching heuristic” (DBH) with a look ahead to do dispatching at a batch processing. Fowler et al. [21] presented the next arrival control heuristic (NACH), which is a modification of DBH that considers only the next arrival. Weng and Leachman [22] use minimum cost rate (MCR) to minimize the WIP and save the inventory cost. Moreover, Robinson et al. [23] proposed the rolling horizon cost rate heuristic (RHCR). Additionally, Van Der Zee et al. [24] combined NACH and MCR to form the dynamic job assignment heuristic (DJAH). The difference between this method and MCR is that it considers not only inventory cost but also other costs, for example setup cost.

3 Dispatching by production flow value

TOC confirms the bottleneck machines determine system performance. The process time of bottleneck machines can be defined as the system resource time. Jobs consuming the system resource time are charged the system resource cost, i.e., equipment depreciation cost. Thus, to distribute system resource costs to products in proportion to the consumption of system resource time is a reasonable method. This method is termed TOC costing in this study. Besides cost estimation, this study intends to estimate job profitability. The production flow value of a job can be calculated through this approach, and thus job priorities can be determined. The PDF dispatching method is developed. Currently, measurements for evaluating the job sequence must be discussed. This discussion is also included in this study.

3.1 Development of the 7-step PFV procedure

The PFV procedure is developed as follows: (1) establishing the bottleneck machine probability for each machine group, (2) estimating the cost of the system resource time (3) estimating system resources time usage for a wafer lot, (4) estimating wafer lot cost, (5) estimating system resource time unit profitability for specific products, (6) estimating job value, and (7) determining job priorities based on production flow value.

(1) Establishing the bottleneck machine probability for each machine group

The bottleneck machine in a system is defined as the machine with the most WIP awaiting processing. The probability, f_k, that machine k is the bottleneck machine, can be derived as

$$f_k = T_{\text{k machine bottleneck}} \Big/ T_{\text{time period}} \tag{1}$$

and $$T_{time\ period} = \sum_{k=1}^{M} T_{k\ machine\ bottleneck}, \tag{2}$$

where $T_{\text{time period}}$ denotes an observation time period, and $T_{\text{k machine bottleneck}}$ represents the time for which machine k is the bottleneck machine during the observation time period. $T_{\text{time period.}}$ The system is assumed to always be running at full capacity, and therefore, there has to be at least one machine with more than or equal to one WIP wafer lot awaiting. This means a system always has a bottleneck machine.

This study uses simulation to obtain the bottleneck machine probability. For a specific case described in Table 2 and 3 in the appendix and a fixed production rate with MBS and FIFO dispatching rules, a series of 360-day-observation-time-window simulation experiments (not including a 30 day warm-up period) were performed with ten replicates. The bottleneck machine in the system changes periodically. This study recorded the total time that each machine spent as the bottleneck machine. Table 1 listed the data of the first ten machines that had a high probability of being the bottleneck machine. Clearly, in this case, the machine group, FLOW has the highest probability, of nearly 40%. NITRIDE follows in second place with probability 21% and PHOTO follows in third place with probability 9%. The fourth, fifth, and sixth ranking machine groups are DRY_MET, DRY_OX, and DRY_OX. The first six machine groups determine 91% of the system resource, while the remaining machine groups do not significantly influence system productivity.

(2) Estimating the cost of a system resource time unit

In a manufacturing system, extra process time on bottleneck machines can increase system productivity, while extra process time on non-bottleneck machines can only increase the WIP and does not increase production. Therefore, bottleneck machine process time thus can be defined as the system resource time. This study suggests that machine depreciation cost is allocated to products in proportion to the consumption of system resources time. This study assumed the indirect cost in a wafer fabrication plant is dominated by equipment depreciation, and other aspects such as staff salary can be neglected. The determination of a unit of the system resources time cost enables the calculation of the indirect cost of a product provided the product consumption of system resources time is known. This study thus defines the cost of a system resources time unit, C_{ps}, is

$$C_{ps} = \sum_{k=1}^{M} C_{dpr,k} \Big/ T_{system\ time} \tag{3}$$

where $C_{dpr,k}$ denotes the depreciation cost of equipment k per year, M represents the total number of the equipments in the plant, and $T_{system\ time}$ is annual plant operating time.

(3) Estimating wafer lot usage of system resources time

Estimating the indirect cost of a product requires estimating system resources time consumption at each process. This study defines a wafer lot or a batch with n lots

Table 1 The bottleneck machine probability distribution

Rank	Type	$T_{\text{k machine bottleneck (hrs)}}$	Standard deviation (hrs.)	95% confidence interval (hrs)	Ratio (%)
1	FLOW	3420	165	(3047,3793)	39.58±0.04
2	NITRIDE	1804	97	(1585,2023)	20.88±0.03
3	PHOTO	762	41	(669,855)	8.82±0.01
4	DRY_MET	567	33	(492,642)	6.56±0.01
5	DRY_OX	508	27	(447,569)	5.88±0.01
6	IMP_HI	473	24	(419,527)	5.47±0.01
7	SPUTTER	272	13	(243,301)	3.15±0
8	ALLOY	175	8	(157,193)	2.03±0
9	IMP_MED	164	7	(148,180)	1.90±0
10	OX_STRT	79	4	(70,88)	0.91±0
11	other 21 machines	416	21	(368,464)	4.81±0.01
	Total	8640			100

of product i at process j processed by machine k consumes system resources time unit, S_{ij},

$$S_{ij} = f_k \times t_{ij} \text{ for single lot job or} \\ S_{ij} = (f_k \times t_{ij})/n \text{ for batch job},$$

where f_k denotes the probability of machine k being the bottleneck machine, and t_{ij} represents the process time of product i at process j. Using this concept, the total system resources time consumed by the wafer lot of product i processed by m steps can be estimated by

$$S_{i,m} = \sum_{j=1}^{m} S_{ij}, \tag{4}$$

where m is the number of steps that the wafer lot has be processed.

For example, a product A wafer lot was processed on machine group for E 10 min and machine group J for 50 min. Moreover, another product B wafer lot was processed on machine group E 50 min and machine group J 10 min. Apparently, both products require the same manufacturing process time. If the bottleneck probability of machine group E is 0.8, and that of machine group J is 0.2, the system resource time units consumed for product A wafer lot is 10×0.8+50×0.2=18 min, while that consumed for the product B wafer lot is 50×0.8+10×0.2=42 min. The ratio of the system resources time consumed for product A versus product B is 3:7. This ratio indicates that the allocation of the system resources depreciation cost to products A and B is 3:7.

(4) Estimating the cost for a wafer lot

Wafer fabrication requires numerous costly and highly sophisticated machines. Since high technology products have very short lifetimes, it normally takes only five years to depreciate a machine. Consequently, direct cost comprises only a very small part of product cost, while machine depreciation costs dominate the product cost. This study ignores the direct cost, and the machine depreciation cost would be used as the indirect cost. As mentioned before, this study divides the equipment depreciation cost among products in proportion to the consumption of system resources time. The total production cost of a product i wafer lot that has undergone m steps of processing can be approximated as follows:

$$C_{i,m} = C_{dir,i,m} + C_{indir,i,m} \approx C_{indir,i,m}, \text{ and}$$

$$C_{indir,i,m} \approx C_{ps} \times S_{i,m}$$

where $C_{i,m}$ denotes the total production cost for a product i wafer lot after m process steps, and $C_{dir,\ i,m}$ represents the total direct production cost for a product i wafer lot after m process steps. Moreover, $C_{indir,\ i,\ m}$ is the indirect production cost for a product i wafer lot that has undergone m processing steps. Additionally, C_{ps} denotes the cost of a system resource time unit (unit: \$/s). Moreover, $S_{i,m}$ represents the system resources time consumed by a product i wafer lot that has been processed m steps. Therefore, the cost of a product i on-line wafer lot after m process steps is

$$C_{i,m} \approx C_{ps} \times S_{i,m}. \tag{5}$$

(5) Estimating the profitability of a system resources time unit for producing a specific product

A wafer production cost depends on system resource time consumption. For different types of products, even if they consume the same system resource time, they have different sale prices, and thus have different profitability. This study defines the profitability per system resource time unit, ρ_i, for a product i as follows:

$$\rho_i \approx (P_i - C_i)/S_i. \tag{6}$$

P_i and C_i denote the sale price and cost for a product i, wafer lot, respectively, and S_i represents the consumption of system resources time in producing a product i wafer lot. For example, the production system includes two machines, machine E and J. The bottleneck probability of machine E is 20%, compared to 80% for J. Two products A and B have the same process time, namely 60 min. Product A consumes 10 min on machine E and 50 min on machine J, while Product B consumes 50 min on machine E and 10 min on machine J. The net profit for product A is \$200, compared to \$2000 for product B. The system resources time consumed by product A is 42 min compared to 18 min for product B. The ratio of the system resources time consumption of the two products is about 2.3, while the net profit ration is 1/10. Consequently, the profitability per unit of system resources time producing product B is 23 times that for producing product A.

$$\begin{aligned}\rho_A : \rho_B &= (P_A - C_B)/S_A : (P_B - C_B)/S_B \\ &= \$200/(10 \times 20\% + 50 \times 80\%) : \\ &\quad \$2000/(50 \times 20\% + 10 \times 80\%) \approx 1 : 23\end{aligned}$$

(6) Estimating job value

Job value is defined as the profitability of a job being completed. Hence, the value of a job, $prf_{i,m}$, is the product of the profitability per unit of system resources time for product i and the total system resource time units consumed by the wafer lot for processes 1 to m, that is

$$prf_{i,m} = \rho_i S_{i,m} \text{ for a lot, or}$$

$$prf_{i,m} = n\rho_i S_{i,m} \text{ for a batch with n lots.} \tag{7}$$

(7) Determining job priorities based on production flow value

Job priority can be determined after estimating job value. The production flow value of a job thus can be estimated by the following equation:

$$fv_{i,m} = prf_{i,m} / t_{i,m}, \qquad (8)$$

where $t_{i,m}$ denotes the job process time for product i at process m. The job priority k can then be assigned to each queue according to the descending order of the job flow value, $fv_{i,m}$. Hence, the next job to be processed in a machine group is always that with the highest flow value among all queues. In doing so, the production flow value should always be maximized.

3.2 Measurements for the evaluating PFV

The PFV rule is designed to maximize the production flow value. A production system should always maintain low average cycle times and WIP inventory cost if it can maximize profits. Hence, the average cycle time and the inventory cost are used as measurements in this study. Besides these two measurements, the average system resources time consumption, the average profitability per system resource time unit, and the ratio of the first half process time vs. the total process time are also discussed too.

(1) This study defines the cycle time as the time period between a wafer lot entering and leaving the system, including the processing time and waiting time. Normally, a batch job with a large batch size has the higher flow value than a job with a small batch size. This study examines whether the PFV can reduce the cycle time of high profit or large batch size jobs.

(2) The WIP inventory cost is another measurement for evaluating system performance. This study develops a WIP inventory cost estimation method based on the TOC costing, i.e.,

$$C_{WIP} = \sum_{j} \sum_{i} n_{ij} \times C_{ps} \times S_{i,j} \qquad (9)$$

where i denotes the product type, j represents the machine group number, and n_{ij} is the number of lots of product i at machine group j.This study examines whether the PFV can reduce system WIP inventory cost.

(3) Average system resource time consumption: Since flow value determines job priority, a batch job involving several low-profit wafer-lots can accumulate considerable profit given sufficient batch size, and thus can have a high job priority. Therefore, using PFV can enable a highly profitable single lot job or a large size batch job to have a high priority for system resources time consumption. Therefore, the average system resources time consumed by a job is also a good measurement for evaluating PFV. This study examines the distribution of system resource time allocation among products.

(4) Profitability of a system resource time unit: A high-profit job or a large batch size job should consume more system resource time. The profitability of a system resource time unit for a high-profit job or a large batch size job should be higher than that for a low-profit job or a small batch size job. This is examined in this study.

(5) Ratio of first half processing time to total processing time: The value of wafers gradually increases with the number of operations processed on them. Thus, the second-half processing time should be less than the first-half processing time for all wafers. This phenomenon is especially notable for highly profitable wafers or those which

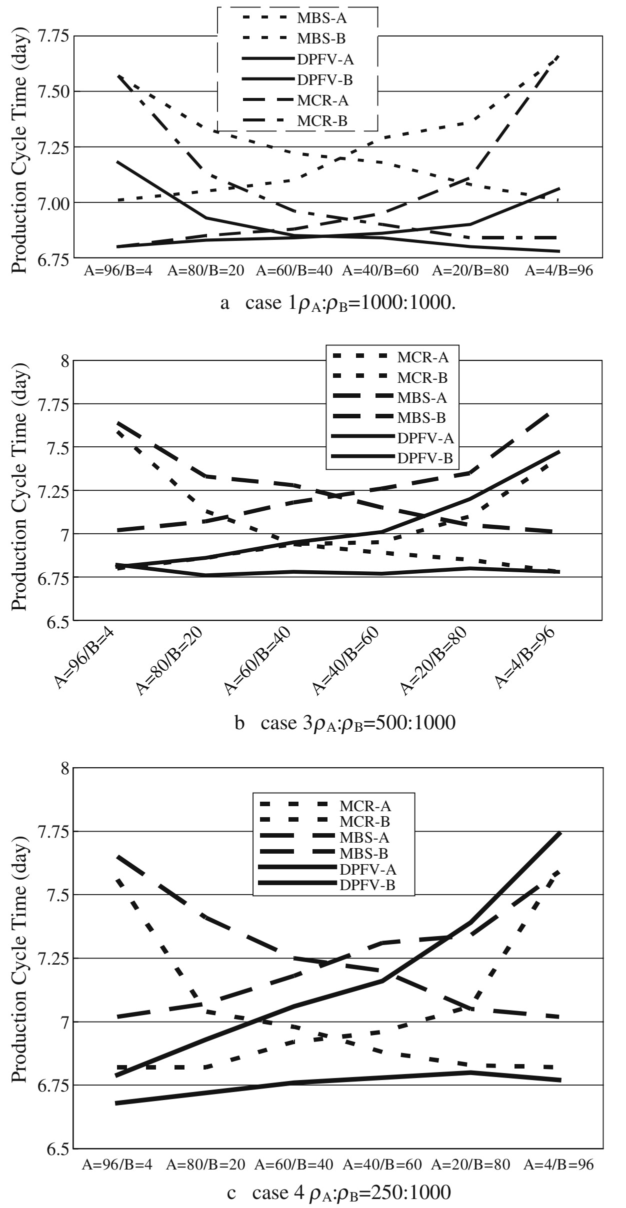


Fig. 1 Average cycle time performance among three methods (a) case 1 ρ_A:ρ_B=1000:1000. (b) case 3 ρ_A:ρ_B=500:1000 (c) case 4 ρ_A:ρ_B=250:1000

easily form a large batch size. If the average first half process time is F min, and the average cycle time is T. The ratio of the first half processing time to the total processing time is rf=F/T×100(%). Obviously, the ratio of the second half processing time to the total processing time is rr=(T−F)/T×100(%)=1−rf. This study examines the ratio, rf.

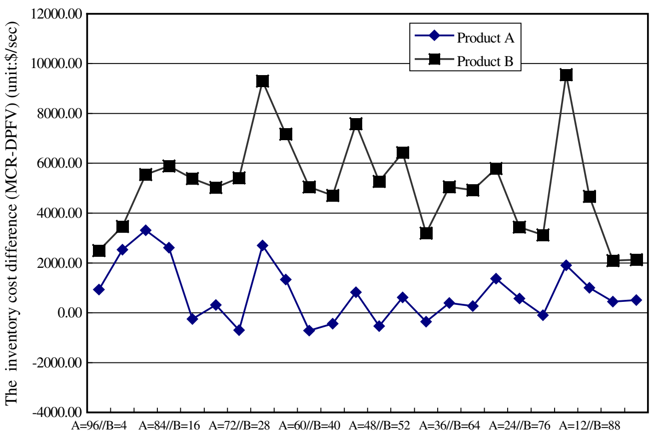
4 Case study

This study adopted the object-oriented eM-Plant tool to establish a wafer fabrication simulation environment. The machine data and wafer recipe are shown in Tables 2 and 3 in the appendixes. Several assumptions are made:

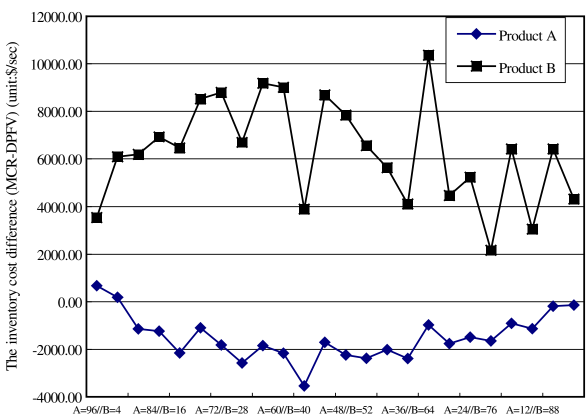
1. Material handling system and workforce always satisfy the manufacturing conditions, and their costs are ignored.
2. The unit applied in this study is a lot, which contains 25 pieces.
3. All the operations produce good products, and there is no need for reworking.
4. All the process times are constant, and the time between machine failures and machine repair time are exponential distributions.
4. Input regulation adopts a constant input rate.
5. The buffer size is infinite.

4.1 Examination of PFV performance

This section assesses PFV performance. For comparative purpose, besides PFV, this study adopts two other batch job dispatching methods, MBS and MCR, and performs simulations. Two products, A and B, are produced. The job release rate of A and B is set to be 96/4, 92/8, 88/12, . . . , 4/96, respectively. Four profitability-ratio cases are discussed: (a) $\rho_{A:}$ ρ_B=1000:1000, (b) $\rho_{A:}$ ρ_B=750:1000, (c) ρ_A: ρ_B=500:1000, and (d) ρ_A: ρ_B=250:1000. Each simulation is to be performed for 24 hours per day over a two year period (not including a 30 day warm up period) and is repeated ten times.

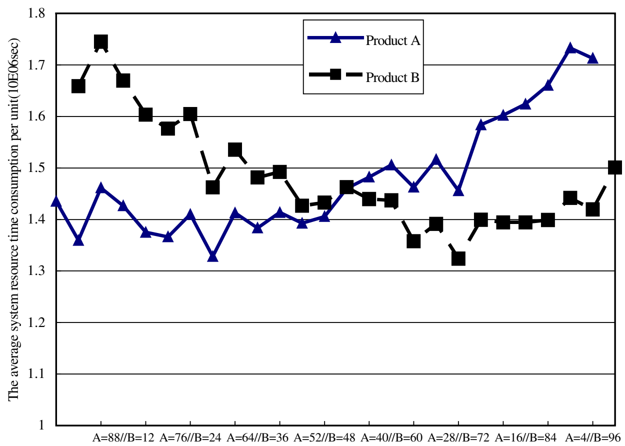


a case 2 ρ_A:ρ_B=750:1000

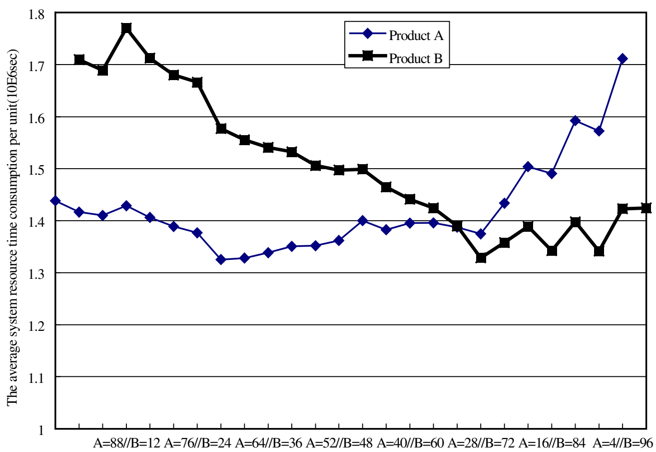


b case 4 ρ_A:ρ_B

Fig. 2 The difference (MCR - PFV) of the WIP inventory cost (a) case 2 ρ_A:ρ_B=750:1000 (b) case 4 ρ_A:ρ_B=250:1000



a case 1 ρ_A:ρ_B=1000:1000



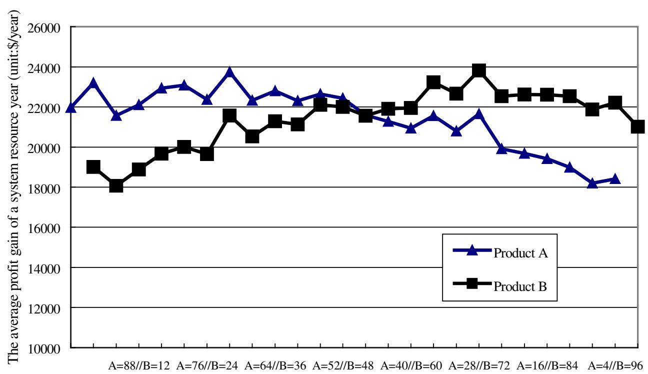
b case 3 ρ_A:ρ_B=500:1000

Fig. 3 The average system resource time consumption of a wafer lot (a) case 1 ρ_A:ρ_B=1000:1000 (b) case 3 ρ_A:ρ_B=500:1000

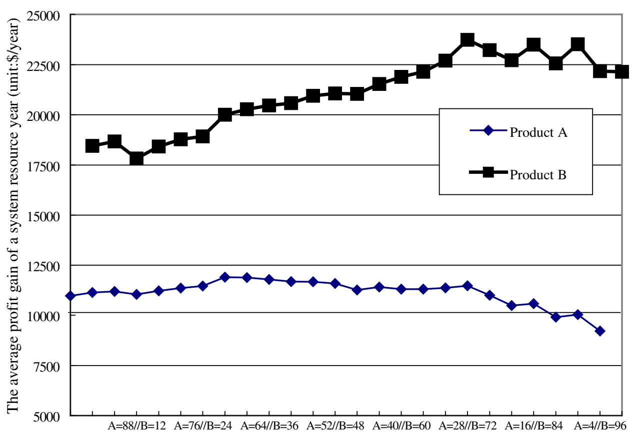
The simulation results are analyzed and discussed from the perspective of the five measurements discussed above.

(1) From the production cycle time: Table 4 in the appendix partially lists the simulation results. The simulation results show that the standard deviations of the average cycle times for all of the cases are between 0.003 and 0.006 days. Hence, we can conclude that the PFV rule achieves the best production cycle time performance of the three methods for case 1, and the performance of PFV for product B remains the best in cases 2, 3, and 4, while its performance for product A steadily deteriorates. In case 4, the performance of PFV for product A is even worst than that of MBS when the release rate of job A drops to 20. In Fig. 1(a), the three rules have symmetrical performances since the profitability ratio is 1:1. In Figs. 1(b) and (c), the performances of MBS and MCR remain symmetrical since they are not related to profitability, while the average cycle times of PFV for product B remain low and those for product A increase with decreasing job release rate. The simulation results indicate that PFV pushes high profit jobs out of the plant hard, while MBS and MCR only push large batch size jobs out of the plant hard. Therefore, PFV maximizes the production flow value, and MBS and MCR only maximize the production rate.

(2) From the WIP inventory cost: The above study shows that MCR performs better than MBS. This section excludes MBS and examines the difference in WIP inventory cost (MCR-PFV) between MCR and PFV. In case one, the differences are always positive for both products A and B. From a statistical point of view, the performance of PFV cannot be concluded to be better than that of MCR in case 1. However, PFV can be concluded to either be as good as or better than MCR in case 1. In the other three cases, for those involving product B, the difference between two dispatching rules becomes an increasing positive value, while for product A, the difference gradually becomes negative, and the positive difference grows much faster than the negative difference owing to change in the profitability and job release rate. This phenomenon occurs because PFV responses to the changes of the profitability and the job release rate, while MCR does not consider the profitability at all and only responses to the

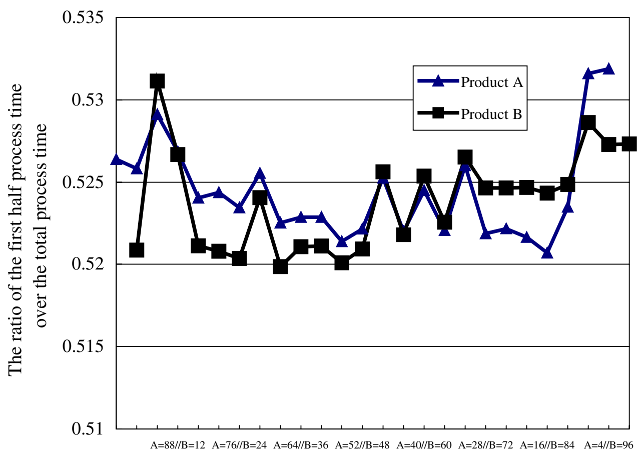


a case 1 ρ_A:ρ_B=1000:1000

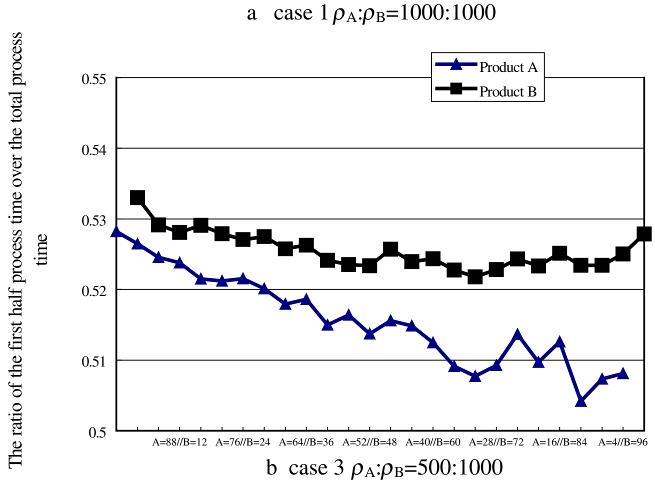


b case 3 ρ_A:ρ_B=500:1000

Fig. 4 The average annual profit gain (a) case 1 ρ_A:ρ_B=1000:1000 (b) case 3 ρ_A:ρ_B=500:1000 :1000



a case 1 ρ_A:ρ_B=1000:1000



b case 3 ρ_A:ρ_B=500:1000

Fig. 5 Ratio of first half process time to total process time (a) case 1 ρ_A:ρ_B=1000:1000 (b) case 3 ρ_A:ρ_B=500:1000 changes in job release rate. Figures 2(a) and (b) show the differences of the WIP inventory cost in cases 2 and 4.

(3) Average system resources time consumption: This section investigates how PFV consumes the system resources time, and the relationship between the system resource time consumptions and profitability. The simulation results show that the system resources time consumption depends on the product job release rate when products A and B have the same profitability. Job batch size is larger for products with a higher job release rate, resulting in low system resources time consumption per unit lot. Job batch size is smaller for products with lower job release rate, resulting in high system resources time consumption per unit lot. For cases that products A and B have different profitability, not only the product job release rate but also the profitability affects the system resources time consumption. Generally, products with higher profitability do not need to form a large batch size job to get a high priority. Hence products with higher profitability but lower job release rate consume high system resource times per unit lot. Products with low profitability need to form a large batch size to get high priority. Products with low profitability consume less system resources time per unit lot. Figure 3 shows the results of cases 1 and 3. In Fig. 3, the intersection point indicates that a unit lot of the product A job consumes the same system resources time as that of the product B job. In Fig. 3(a), the intersection point is in the middle. Moreover, in Fig. 3(b), the intersection point is moving to the right. This phenomenon indicates that a unit lot of a job with lower profitability and high job release rate consumes less system resources time than that another job with higher profitability and low job release rate.

(4) System resources time unit profitability: Because a system resource time unit has low profitability, this study investigates the annual profit gain instead. This study illustrates the results of two cases, cases 1 and 3, in Figs. 4 (a) and (b). The trend of the profit gain shows that the product job release rate and the profitability are positively correlated with the profit gain. Products with high job release rate or/and high profitability are more profitable than those with low job release rate or/and low profitability per time unit.

(5) Ratio of first half processing time to total processing time: This study deals with a 61-step recipe for wafer fabrication. The whole process is separated into two parts, the first half (steps 1 to 30) and the second half process (steps 31 to 61). The results show that the ratio of the first half process time over the total process time always exceeds 50%. The ratio of first half processing time to total processing time for those products besides products with lower profitability and with lower job release rate is between 52% and 53%, and the ratio of first half processing time to total processing time for products with lower profitability is gradually reduced to near 50% with decreasing job release rate. The simulation results show that PFV pushes wafer lots with high profitability during the second-half process period out of the plant harder than those with low profitability during the second-half process period. This study illustrates the changes of the ratio of first half processing time to total processing time for cases, $\rho_A:\rho_B$=1000:1000 and $\rho_A:\rho_B$=500:1000 in Fig. 5(a) and (b).

The simulation results demonstrate that PFV can effectively manage the system resources time for jobs with different profitability and batch size to ensure that the production flow value is maximized.

5 Conclusions

This study proposed a production-flow-value-based job dispatching rule, PFV. This study uses the theory of constraints as a basis for defining the system resources time and initiates a TOC product costing. This study derives an estimation method to estimate the cost of the consumption of a system resources time unit, and enabling the cost of a WIP wafer lot to be estimated. If the sale price of a wafer product is known, then the profitability of a single wafer lot or a batch job can be estimated, thus enabling the derivation of the production flow value for each job. The job with the highest production flow value is always picked up and processed first. Therefore, the proposed PFV job dispatching rule can always maximize the production flow value, thus maximizing the profit.

A simulation model is built for demonstration purposes. Besides the purposed PFV method, MBS and MCR are used as dispatching rules, respectively, in the simulations. The simulation results reveal that PFV shortens production cycle times for products with high-profitability or/and high job release rate, and effectively reduces the cost of WIP inventory. PFV allows products with high-profitability to consume more system resources time, and generate more profit. Therefore, PFV maximizes the production flow value, while MCR and MBS do not.

Acknowledgements The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC90-2212-E-002-210.

1 Appendix

Table 2 Table 3 Table 4

Table 2 Machine data (MTBF and MTTR represent mean time between failure and mean time to repair, both are exponential distributions)

Machine No.	Machine type	Q'ty	Batch size(lot)	MTBF (hrs)	MTTR (mins)
1	ALLOY	3	6	4	24
2	BK_PO	1	1		
3	BPSG	2	1		
4	CAP_OX	1	1		
5	DRY_MET	3	1		
6	DRY_OX	2	1		
7	DRY_PA	2	1		
8	DRY_PO	3	1		
9	DRY_SI	1	1		
10	DRY_SN	2	1	0.8	8
11	DRY_SW	1	1		
12	FLOW	2	6	4	24
13	GATE_OX	1	1		
14	GRIND	1	1		
15	HP_4062U	1	1		
16	IMD	2	1	2	30
17	IMP_HI	1	1	2	30
18	IMP_MED	1	1		
19	INTER_OX	1	1		
20	MARKED	1	6	4	24
21	NITRIDE	1	1		
22	OX_FLD	3	6	4	24
23	OX_GATE	3	6	4	24
24	OX_SD	4	6	4	24
25	OX_STRT	15	6	4	24
26	PESN	2	1		
27	PHOTO	9	1	0.75	5.5
28	POCL	3	6	4	24
29	POLY	3	6	4	24
30	QA_SCOPE	1	1		
31	SD_OX	1	1		
32	SCUBBER	2	6	4	24
33	SOG	1	1		
34	SPUTTER	8	1		
35	TEOS	3	6	4	24
36	UV_ERASE	1	1		
37	WCVD	1	1		
38	WELL_DRV	3	6	4	24
39	WET_SN	1	1		

Table 3 A 61-step product recipe used in the study (We assume all the process times are constant)

Step No.	Machine No.	Process time (unit:hour:min:sec)	Rework?	Step No.	Machine No.	Process time (unit:hour:min:sec)	Rework
1	32	2:52:08.4000	0	33	24	45:16.0000	0
2	25	7:07:12.0000	0	34	27	48:02.4000	1
3	21	47:21.0000	0	35	17	45:16.2000	0
4	27	48:02.4000	1	36	27	48:02.4000	1
5	10	57:43.2000	0	37	17	45:16.2000	0
6	18	15:54.0000	0	38	3	2:37:15.0000	0

Table 3 (continued)

Step No.	Machine No.	Process time (unit:hour:min:sec)	Rework?	Step No.	Machine No.	Process time (unit:hour:min:sec)	Rework
7	22	4:16:42.0000	0	39	12	4:16:42.0000	0
8	39	34:33.6000	0	40	27	1:00:28.8000	1
9	18	15:54.0000	0	41	6	1:26:24.0000	0
10	38	4:16:42.0000	0	42	12	47:21.0000	0
11	25	7:07:12.0000	0	43	34	5:45:36.0000	0
12	21	47:21.0000	0	44	27	49:46.2000	1
13	27	1:00:28.8000	1	45	5	2:09:57.0000	0
14	10	57:43.2000	0	46	16	1:10:30.0000	0
15	27	48:02.4000	1	47	33	1:02:12.6000	0
16	18	15:54.0000	0	48	16	1:10:30.0000	0
17	8	1:44:43.2000	0	49	27	1:00:28.2000	1
18	39	34:33.6000	0	50	6	1:26:24.0000	0
19	25	7:07:12.0000	0	51	34	5:45:36.0000	0
20	27	48:02.4000	1	52	27	48:02.4000	1
21	18	15:54.0000	0	53	5	2:24:07.2000	0
22	23	4:16:42.0000	0	54	26	1:10:30.0000	0
23	29	4:16:42.0000	0	55	26	1:09:48.6000	0
24	2	1:06:00.6000	0	56	27	48:02.4000	1
25	28	4:16:42.0000	0	57	7	2:01:18.6000	0
26	27	1:00:28.8000	1	58	1	4:16:42.0000	0
27	8	1:44:43.0000	0	59	15	1:16:43.2000	0
28	24	4:16:42.0000	0	60	14	56:40.8000	0
29	27	48:24.0000	1	61	30	1:26:24.0000	0
30	18	15:54.0000	0				
31	35	4:16:42.0000	0				
32	11	1:09:07.2000	0				

Table 4 The average cycle times for the three dispatching rules from the simulation results (Note the standard deviations for all of the results are between 0.003~0.006days.)

Profitability ρ_A:ρ_B	Job release ratio	MCR		MBS		PFV	
		Product A CT (day)	Product B CT (day)	Product A CT (day)	Product B CT (day)	Product A CT (day)	Product B CT (day)
1000:1000	A=96//B=4	6.80	7.57	7.01	7.57	6.80	7.18
	A=80//B=20	6.85	7.13	7.05	7.33	6.83	6.93
	A=64//B=36	6.88	6.99	7.14	7.25	6.85	6.90
	A=48//B=52	6.94	6.94	7.25	7.21	6.84	6.84
	A=32//B=68	6.97	6.83	7.3	7.13	6.89	6.84
	A=16//B=84	7.11	6.82	7.39	7.04	6.93	6.81
	A=4//B=96	7.66	6.84	7.65	7.01	7.06	6.78
750:1000	A=96//B=4	6.79	7.48	7.03	7.71	6.78	6.86
	A=80//B=20	6.86	7.12	7.08	7.43	6.86	6.85
	A=64//B=36	6.93	7.03	7.18	7.34	6.90	6.83
	A=48//B=52	6.92	6.91	7.23	7.2	6.93	6.81
	A=32//B=68	7.02	6.88	7.29	7.11	7.01	6.80
	A=16//B=84	7.23	6.89	7.5	7.09	7.07	6.78
	A=4//B=96	7.49	6.79	7.69	7.01	7.32	6.77

Table 4 (continued)

Profitability $\rho_A:\rho_B$	Job release ratio	MCR		MBS		PFV	
		Product A CT (day)	Product B CT (day)	Product A CT (day)	Product B CT (day)	Product A CT (day)	Product B CT (day)
500:1000	A=96//B=4	6.8	7.59	7.02	7.64	6.81	6.82
	A=80//B=20	6.86	7.13	7.07	7.33	6.86	6.76
	A=64//B=36	6.92	7.02	7.14	7.29	6.93	6.77
	A=48//B=52	6.91	6.9	7.21	7.19	6.99	6.78
	A=32//B=68	6.97	6.86	7.27	7.11	7.08	6.79
	A=16//B=84	7.1	6.8	7.54	7.11	7.25	6.80
	A=4//B=96	7.43	6.78	7.73	7.01	7.47	6.78
250:1000	A=96//B=4	6.82	7.56	7.02	7.65	6.79	6.68
	A=80//B=20	6.82	7.04	7.07	7.41	6.93	6.72
	A=64//B=36	6.9	7.01	7.09	7.22	7.01	6.75
	A=48//B=52	6.92	6.91	7.24	7.22	7.11	6.76
	A=32//B=68	7.08	6.93	7.28	7.1	7.21	6.78
	A=16//B=84	7.18	6.86	7.4	7.04	7.51	6.78
	A=4//B=96	7.6	6.82	7.59	7.08	7.74	6.77

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