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An application of AHP and sensitivity analysis for selecting the best slicing machine

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Abstract

Wafer slicing is a complex manufacturing process, complicating efforts to monitor process stability and quality control effectively. This study discusses and develops a manufacturing quality yield model for forecasting 12 in. silicon wafer slicing based on the Analytic Hierarchy Process (AHP) framework. Decision Makers can select evaluation outcomes to identify the most precise machine. Additionally, EWMA control chart is presented to demonstrate and verify the feasibility and effectiveness of the proposed AHP-based algorithm. Finally, sensitivity analysis is performed to test the stability of the priority ranking. Therefore, this work illustrates how the AHP model would be implemented to help engineers determine the manufacturing process yield quickly and effectively.

Keywords: Silicon wafer slicing; Analytical Hierarchy Process; EWMA; Sensitivity analysis

1. Introduction

The pervasiveness of electronic products and Internet-based technologies has contributed significantly to the accelerated development and global competitiveness of the Taiwanese semiconductor industry. Semiconductor manufacturers require wafers with larger diameter and more stringent technical specifications to produce increasingly complex semiconductor devices such as larger megabit memory chips and microprocessors (Lin, Chang, & Chen, 2006). The 12 in. wafer slicing is currently the most challenging process in semiconductor manufacturing in terms of controlling yield. Since silicon wafer slicing directly impacts production costs, increasing and maintaining wafer yield, as well as understanding the factors that contribute to declining yields are key concerns among semiconductor manufacturers.

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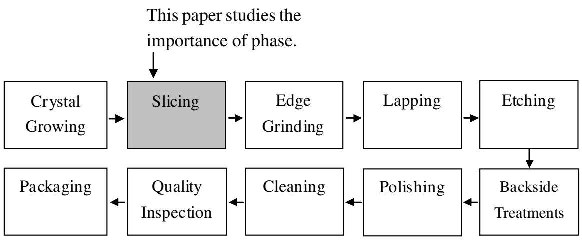

Fig. 1. Silicon wafer manufacturing process.

Previous studies on product quality in semiconductor manufacturing have largely adopted statistical methods to examine either wafer yield or how process engineers select the process parameters of wafer yield based on their subjective experiences. Statistical or experimental design methods have then been applied to analyze the results. However, semiconductor manufacturing includes thousands of process parameters that influence one another, making it extremely difficult to identify the key influences. Cunningham, Spanos, and Voros (1995) indicated that, although conventional statistical and experimental design methods have enhanced wafer yield, statistical methods suffer many limitations with respect to complex mutual influence and the non-linear problem. Additionally, Braha and Shmilovici (2002) found that given the large number of parameters used in semiconductor manufacturing, statistical methods could not efficiently analyze useful decision information.

The wafer manufacturing process needs to be performed in a clean room, as shown in Fig. 1. However, wafer slicing yield is the most difficult variable to control. Slicing describes the cut of silicon ingots into slices. This is usually done using a diamond saw. Each of the wafers is then polished until they are very smooth and just the right thickness. A wafer can be easily broken during inspection owing to its thinness and brittleness. Therefore, to make smaller crooked wafer to meet client demand advanced slicing machines are used (Kao, Prasad, & Li, 1997). Lin, Chen, and Chang (2002) studied silicon wafer slicing as a complex manufacturing process, and proposed that the slicing process involves several synchronously occurring multiple quality characteristics, such as thickness (THK) (ASTM F657, 1995), bow (ASTM F534, 1995), warp (Takeshi, 1998), total indicator reading (TIR) (Takeshi, 1998) and total thickness variation (TTV) (Takeshi, 1998), which must be closely monitored and controlled. Lin, Chang, and Chen (2004) investigated the slicing cutting procedure, which has difficulty in yielding the required precision. Lin used focus groups to identify the main influences on the quality of the manufacturing process, with the factors identified including machinery, personnel, management, measurement and so on. Identifying negative influences can avoid unstable operations during slicing and the production of incorrect quantities. Pai, Lee, and Su (2004) also deemed that the complexity and variability of wafer fabrication creates major difficulties in the relevant production management. Notably, Lin, Chang, and Chen (2005) applied the Chinese philosophy of yin and yang to illustrate issues involving wafer production management and controlling wafer slicing quality, and provided decision makers with philosophical concepts to help them balance the simultaneous consideration of various factors. Furthermore, to increase process yield and accurately forecast next wafer slice quality, grey forecasting is applied to constantly and closely monitor slicing machine drift and quality control.

This study presents a modified Delphi method to develop an evaluation framework. The AHP algorithm is used to evaluate three kinds of cutting machines and identify the machine with the optimum precision. Additionally, the EWMA control chart demonstrates the effectiveness of the proposed AHP method in selecting the evaluation outcomes and assessing the precision of the optimal performing machines. Finally, the sensitivity analysis is performed to test the stability of the rank order. The rank order can devise a standard operational procedure for ensuring quality yield in the semiconductor industry.

2. Method application and results

AHP is a method for decision formulation and analysis (Saaty, 1990). Yang, Su, and Hsu (2000) applied AHP to determine systematic layout planning on semiconductor wafer fabrication facilities. Moreover, Hwang (2004) proposed three steps to evaluate web-based multi-attribute model for engineering project. Ho (2004) applied the AHP model to strategically evaluate emerging technologies in the semiconductor foundry industry. Furthermore, Yurdakul (2004) adopted AHP for selecting machine tool alternatives so as to help the manufacturing strategy of a manufacturing organization. AHP has thus been successfully applied to a diverse array of problems. The process proposed in this study for selecting the optimal machine in terms of precision comprises the following steps.

2.1. Step 1: Define the evaluative criteria used to select the optimal performing machine in terms of precision, and establish a hierarchical framework

The Delphi method consists of five procedures: (a) Select the anonymous experts; (b) Conduct the first round of a survey; (c) Conduct the second round of a questionnaire survey; (d) Conduct the third round of a questionnaire survey; (e) Integrate expert opinions to reach a consensus. Steps (c) and (d) are normally repeated until a consensus is reached on a particular topic (Delbecq, Van de Ven, & Gustafson, 1975). Results of the literature review and expert interviews can be used to identify all common views of survey and simplify the step (b) to replace the tradition opening style survey. Simplifying above process is called the modified Delphi method (Murry & Hammons, 1995). Therefore, this article employs the modified Delphi method to evaluate criteria and sub-criteria, and through anonymous expert interview and survey of outcome direct to focus the research subject.

Delbecq et al. (1975) pointed out the suitable members of Delphi method group should involve five to nine persons. Murry and Hammons (1995) suggested that the modified Delphi method must summarize expert opinions on a range from 10 to 30. Therefore, administrators and engineers from thirteen wafer factories were then issued a preliminary questionnaire in which four evaluation criteria and eleven evaluation sub-criteria were incorporated. Each criterion was defined in terms of operation (Table 1).

Table 1
Operational type for defining criteria and sub-criteria factors

	Code name	The operating type defining
Criteria		
Machine-related	(C_1)	The defective rate is owing to the machine
Human-related	(C_2)	Human factors result in the reason of the slice defective rate
Management	(C_3)	Implement the goal to ensure the process yield of the wafer slice
Measurement	(C_4)	Balance the approaches of wafer slicing using a relevant measurement procedure
Sub-criteria		
Wire knife life cycle	(CS_1)	The wire knife life has serious influence in its processing capability. As the wire knife is still used under the state of scrap item, it tends to produce injured knife and cause chip defective rate
Machine precision	(CS_2)	Because of using machine for a long time, the accuracy of machine becomes worse that will influence the chip quality and the yield after processing
Parameters setting	(CS_3)	A bad setting of the machine parameter would influence the process capability
Establish adjusting standard procedures	(CS_4)	Establishing a suit of managements of the standard process would make the staff deal with the problem s of the process in order
Engineer's experience	(CS_5)	An engineer has to accept the whole in-service training before working and has to possess the related technique knowledge so that operating the machine practically and raising the product yield
Adjusting time	(CS_6)	Proofreading regularly could guarantee the process capability
Color management	(CS_7)	Use color management to enable not only staff but the raw material and the control of the poor yield could be conducted
Online education	(CS_8)	On-line training could enhance professional knowledge and engineering expertise, as well as reduce the errors of the artificial importation and increase productivity
Multi-response	(CS_9)	Adequate control is available for the multiple quality characteristics, which could effectively determine the optimum factor-level combinations and raise the proficiency of the wafer slicing process
Method to check	(CS_{10})	A verification method to achieve the most reliable measurement would effectively promote the ability and proficiency of the process
Measure characteristic	(CS_{11})	Formulating the measurement quality characteristics could reduce engineering errors; otherwise, the characteristics of errors could be easily identified

Based on the modified Delphi method, a general consensus among experts can be reached to establish a hierarchical structure. The optimal performing machine in terms of precision can be selected and evaluated based on four evaluation criteria, eleven evaluation sub-criteria and, finally, the alternatives (Fig. 2).

2.2. Step 2: Establish each factor of the pair-wise comparison matrix

In this step, the elements of a particular level are compared pair-wise, with respect to a specific element in the immediate upper level. A judgment matrix is formed and used for computing the priorities of the corresponding elements. First, a criterion is compared pair-wise with respect to the goal. The judgment matrix, denoted as A, will be formed using the comparison. Let $A_l, A_2, \ldots, A_n$, be the set of stimuli. The quantified judgments on pairs of stimuli A_i, A_j, are represented by

$$A = [a_{ij}], \quad i,j = 1,2,\ldots,n. \tag{1}$$

The comparison of any two criteria C_i and C_j with respect to the goal is made using the questions of the type: of the two criteria C_i and C_j which is more important and how much. Saaty (1980) suggests the use of a 9-point scale to transform the verbal judgments into numerical quantities representing the values of a_{ij}. Table 2 lists the definition of 9-point scale. Larger number assigned to the pair-wise comparisons means larger differences between criteria levels. The entries a_{ij} are governed by the following rules:

$$a_{ij} > 0, \quad a_{ji} = \frac{1}{a_{ij}}, \quad a_{ii} = 1 \quad \text{for all } i. \tag{2}$$

This scale can be applied with ease to criteria that can be defined numerically as well as to those cannot be defined numerically. Relative importance scale is presented. The decision maker is supposed to specify their judgments of the relative importance of each contribution of criteria towards achieving the overall goal.

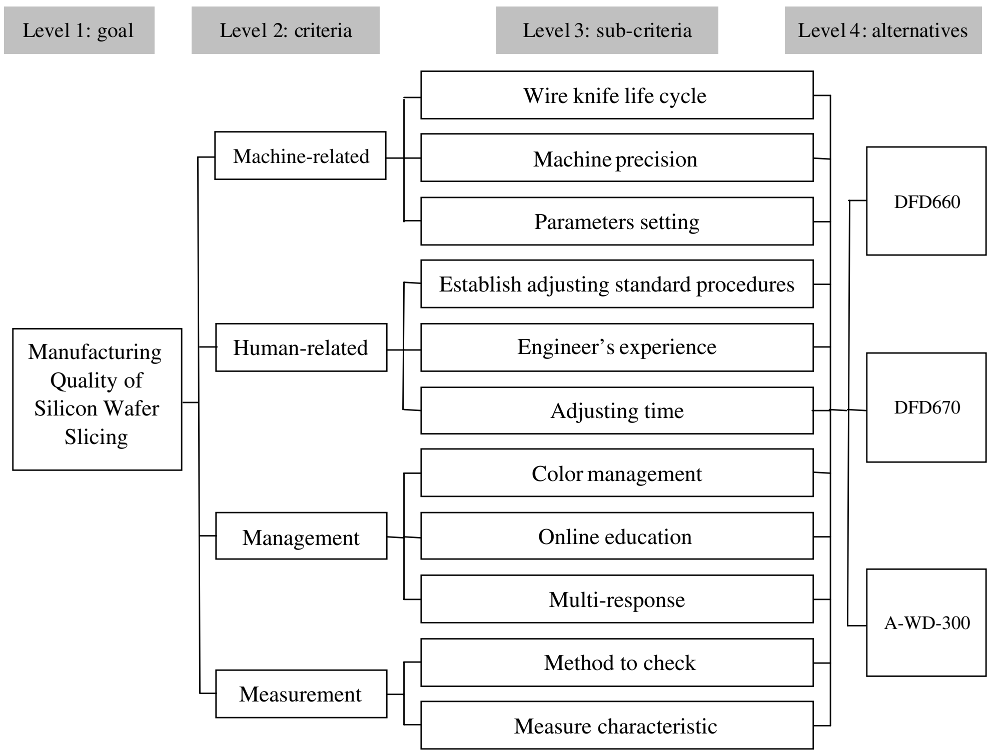

Fig. 2. Hierarchical structure to select the manufacturing quality of silicon wafer slicing.

Table 2
The pairwise comparison scale (Saaty, 1980)

Intensity of importance	Definition
1	Equal importance both element
3	Weak importance one element over another
5	Essential or strong importance one element over another
7	Demonstrated importance one element over another
9	Absolute importance one element over another
2, 4, 6, 8	Intermediate values between two adjacent judgments

For this reason, a questionnaire was devised to find out an expert opinion in the form of a pair-wise comparison. Therefore, purposive sampling is applied to sample sixteen respondents comprised of administrators and engineers from wafer factories. Based on the weighted value that experts finally assign, the geometry mean value is used to compute decision-making community scores of all experts in order to formulate the weighted values selected for silicon wafer slicing manufacturing quality. Table 3 presents the main criteria as the sample.

2.3. Step 3: Calculate the eigenvalue and eigenvector

Having recorded the numerical judgments a_{ij} in the matrix A, the problem now is to recover the numerical weights (W_1, $W_2,\ldots,$ W_n) of the alternatives from this matrix. In order to do so, consider the following equation:

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \simeq \begin{bmatrix} W_1/W_1 & W_1/W_2 & \cdots & W_1/W_n \\ W_2/W_1 & W_2/W_2 & \cdots & W_2/W_n \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ W_n/W_1 & W_n/W_2 & \cdots & W_n/W_n \end{bmatrix}. \tag{3}$$

Moreover, let us multiply both matrices in Eq. (3) on the right with the weights vector $W = (W_1, W_2,\ldots, W_n)$, where W is a column vector. The result of the multiplication of the matrix of pair-wise ratios with W is nW, hence it follows:

$$AW = nW. \tag{4}$$

This is a system of homogenous linear equations. It has a non-trivial solution if and only if the determinant of $A - nI$ vanishes, that is, n is an eigenvalue of A. I is an $n \times n$ identity matrix. Saaty's method computes W as the principal right eigenvector of the matrix A; that is,

$$AW = \lambda_{\max} W, \tag{5}$$

where $\lambda_{\max}$ is the principal eigenvalue of the matrix A. If matrix A is a positive reciprocal one then $\lambda_{\max} \geqslant n$, (Saaty, 1990). If A is a consistency matrix, eigenvector X can be calculated by

Table 3
Aggregate pair-wise comparison matrix for criteria of level 2

Goal	C_1	C_2	C_3	C_4
C_1	1	1.909	0.951	1.147
C_2	0.524	1	1.582	1.622
C_3	1.052	0.632	1	1.026
C_4	0.872	0.616	0.975	1

$\lambda_{\max} = 4.149056$; CI = 0.049685; RI = 0.90; CR = 0.055206 $\leqslant$ 0.1

$$(A - \lambda_{\max} I)X = 0. \tag{6}$$

Here, using the comparison matrix (such as in Table 3), the eigenvectors were calculated by Eqs. (5) and (6). Table 4 summarizes the results of the eigenvectors for criteria, sub-criteria and three diamond cutting machines. Besides, the results for each level relative weight of the elements are showed in Table 4.

2.4. Step 4: Perform the consistency test

The eigenvector method yields a natural measure of consistency. Saaty (1990) defined the consistency index (CI) as

$$\mathrm{CI} = (\lambda_{\max} - n)/(n-1), \tag{7}$$

where $\lambda_{\max}$ is the maximum eigenvalue, and n is the number of factors in the judgment matrix. Accordingly, Saaty (1990) defined the consistency ratio (CR) as

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI}, \tag{8}$$

for each size of matrix n, random matrices were generated and their mean CI value, called the random index (RI). Where RI represents the average consistency index over numerous random entries of same order reciprocal matrices. The consistency ratio CR is a measure of how a given matrix compares to a purely random matrix in terms of their consistency indices. A value of the consistency ratio $\mathrm{CR} \leqslant 0.1$ is considered acceptable. Larger values of CR require the decision-maker to revise his judgments.

According to Eqs. (7) and (8) the criteria comparison matrix of consistency for each criterion is calculated, as shown in Table 3. Results of the consistency test and the CR of the comparison matrix from each of the thirteen experts are all $\leqslant 0.1$, indicating "consistency". Furthermore, the CR of the aggregate matrix is also $\leqslant 0.1$, also indicating "consistency".

2.5. Step 5: Calculate the overall level hierarchy weight to select the optimal performing machine in terms of precision

The composite priorities of the alternatives are then determined by aggregating the weights throughout the hierarchy. The composite priorities of the alternatives are showed in Table 5. According to Table 5, "DFD670" is used to select the evaluation outcomes and evaluate the optimal performing machine in terms of precision.

Table 4
Weights of the criteria, sub-criteria and three diamond cutting machines

Criteria	Weights of criteria	Sub-criteria	Weights of sub-criteria	Synthesis value	DFD660	DFD670	A-WD-300
C_1	0.301	CS_1	0.285	0.085	0.198	0.510	0.292
		CS_2	0.323	0.096	0.360	0.342	0.298
		CS_3	0.392	0.117	0.262	0.409	0.329
		Synthesis value			0.278	0.415	0.307
C_2	0.269	CS_4	0.298	0.079	0.358	0.310	0.332
		CS_5	0.382	0.103	0.314	0.360	0.326
		CS_6	0.320	0.085	0.341	0.362	0.297
		Synthesis value			0.338	0.341	0.321
C_3	0.220	CS_7	0.250	0.056	0.327	0.430	0.243
		CS_8	0.348	0.078	0.177	0.464	0.359
		CS_9	0.402	0.091	0.361	0.347	0.293
		Synthesis value			0.287	0.408	0.303
C_4	0.210	CS_{10}	0.453	0.095	0.345	0.418	0.236
		CS_{11}	0.547	0.116	0.352	0.355	0.293
		Synthesis value			0.349	0.390	0.261

Table 5
Selection of the optimal performing machine in terms of precision in silicon wafer slicing

Criteria	Weights	Synthesis value		
		DFD660	DFD670	A-WD-300
C_1	0.301	0.278	0.415	0.307
C_2	0.269	0.338	0.341	0.321
C_3	0.220	0.287	0.408	0.303
C_4	0.210	0.349	0.390	0.261
Result	Aggregate score	0.311	0.389	0.300
	Rank	***2***	***1***	***3***

2.6. Step 6: Perform EWMA verifying analysis of previous AHP step results

The process standard deviation, σ, is estimated using the X chart and, then, $\lambda = 0.3$ and $n = 2$ are set to monitor and inspect the bow of three diamond cutting machines (DFD660, DFD670 and A-WD-300). In this chart, 133 samples are generated while the process is controlled. Using EWMA (Robert, 1959), the upper and lower control limits for the EWMA statistics are used to calculate the bow of three diamond cutting machines. In Fig. 3, the out-of-control conditions appear at the 12th, 20th, 33rd, 47th and 61st signals. In Fig. 4, the

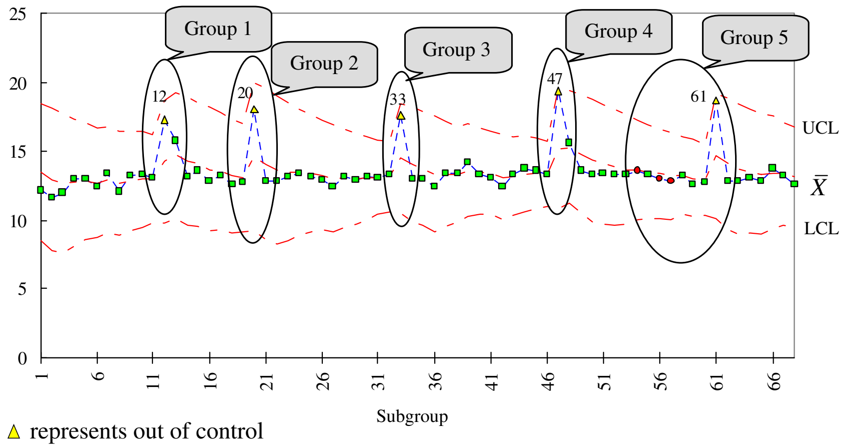

Fig. 3. Upper side of “DFD660” Bow’s EWMA Chart by X Counts.

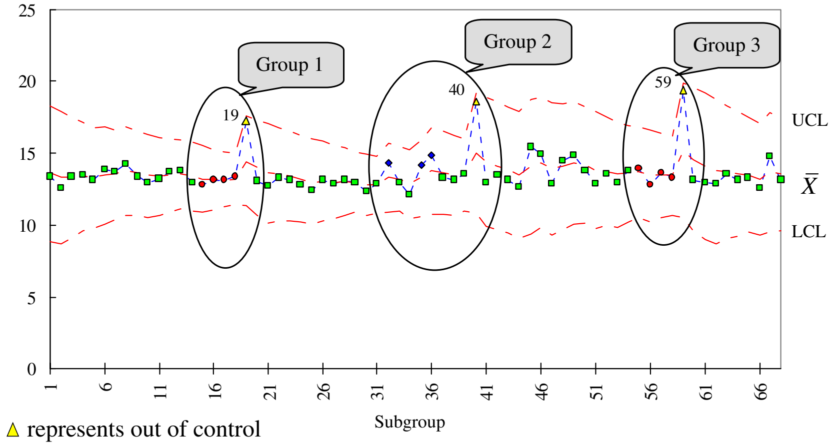

Fig. 4. Upper side of “DFD670” Bow’s EWMA Chart by X Counts.

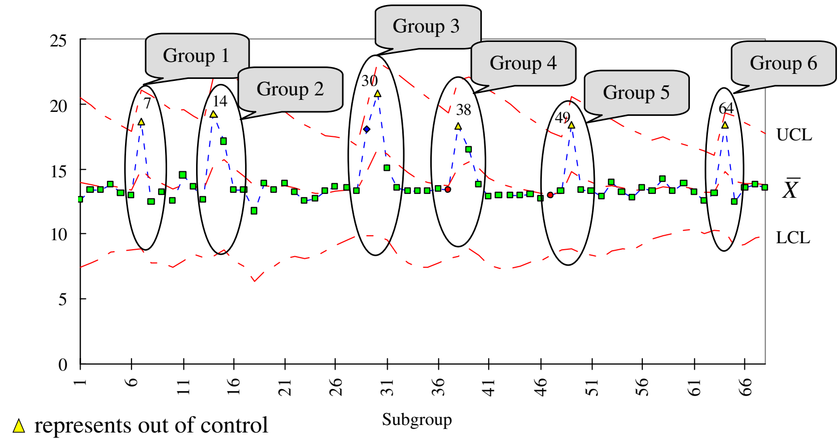

Fig. 5. Upper side of "A-WD-300" Bow's EWMA Chart by X Counts.

process is out-of-control at the 19th, 40th and 59th signals. In Fig. 5, the process is out-of-control at the 7th, 14th, 30th 38th, 49th, and 64th signals. Unusual operating conditions of the manufacturing process appear in DFD670 diamond cutting machines less. Such identification significantly enhances the quality yield of silicon wafer slicing manufacturing. Consequently, the quality of the EWMA chart for the bow verifies the analysis results, in which the AHP results are the same. Based on the evaluation outcomes, "DFD670" is determined to be the optimal performing machine in terms of precision.

3. Perform sensitivity analysis

The final priorities of the alternatives are highly dependent on the weights attached to the main criteria. Small changes in the relative weights can therefore cause major changes of the final ranking. Since these weights are usually based on highly subjective judgments, the stability of the ranking under varying criteria weights has to be tested. For this purpose, sensitivity analysis can be performed based on scenarios that reflect alternative future developments or different views on the relative importance of the criteria. Through

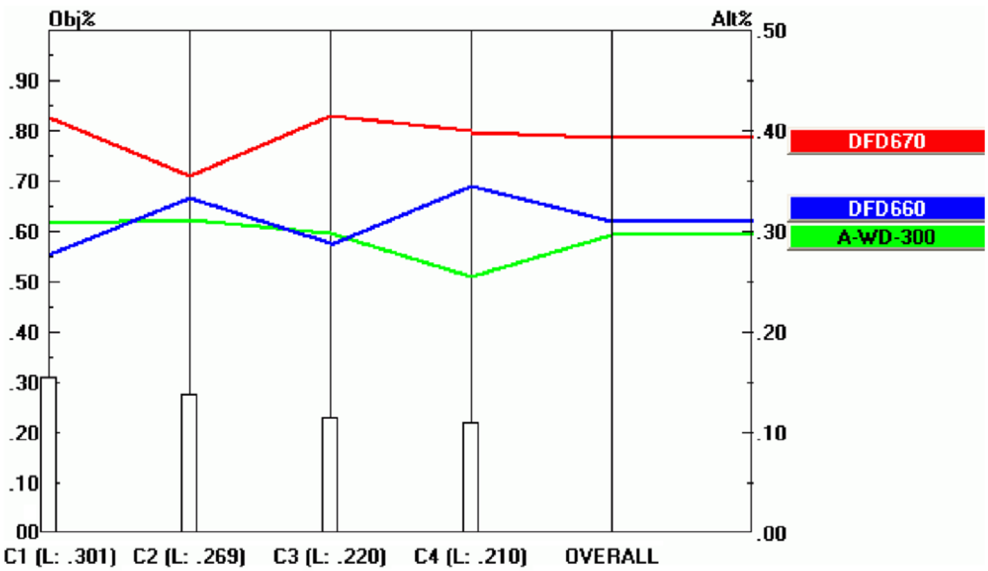

Fig. 6. Performance sensitivity of alternative.

increasing or decreasing the weight of individual criteria, the resulting changes of the priorities and the ranking of the alternatives can be observed. Sensitivity analysis therefore provides information on the stability of the ranking. If the ranking is highly sensitive to small changes in the criteria weights, a careful review of the weights is recommended. Also, additional decision criteria should be included as a highly sensitive ranking point to a weak discrimination potential of the present set of criteria. For this purpose, the weights of the important criteria are separately altered, simulating weights between 0% and 100% (note that the weights of the other criteria change accordingly, reflecting the relative nature of the weights, i.e., the total weights has to add up to 100% in this paper). Sensitivity analyses are necessary because changing the importance of criteria requires various levels of machine-related, human-related, management and measurement with respect to selecting the optimal performing machine in terms of precision in silicon wafer slicing.

Variations in the local priority weights of chosen subjective factors are varied by using Expert Choice 2000 2nd Edition software. The performance graph (Fig. 6) displays how the alternatives perform with respect to

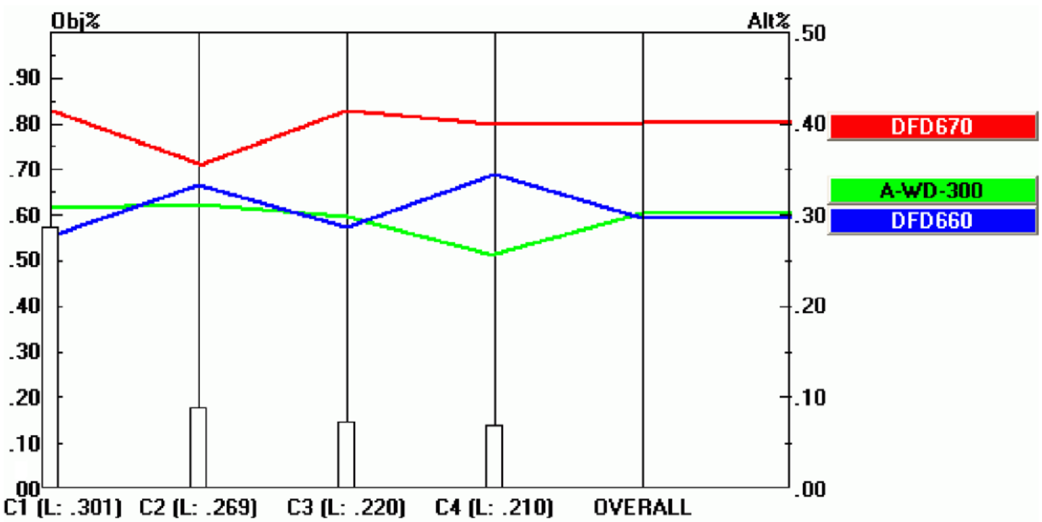

Fig. 7. Performance sensitivity of alternatives when machine-related (C_1) is increased by 25%.

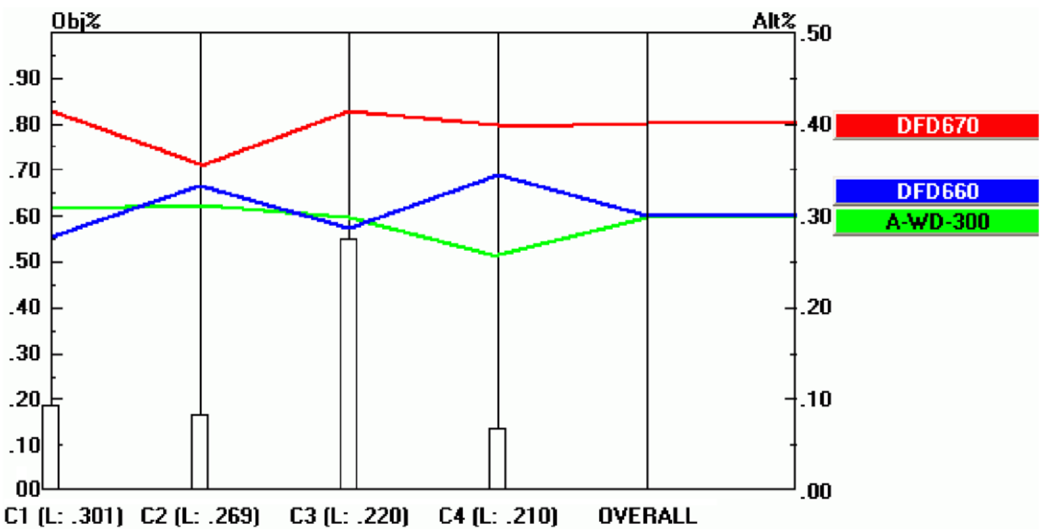

Fig. 8. Performance sensitivity of alternatives when management (C_3) is increased by 30%.

the change in scenario of all parameters. Performance sensitivity of alternatives has been analyzed when machine-related (C_1) is increased by 25%, management (C_3) is increased by 30% and measurement (C_4) is increased by 35% from its current level. Increasing machine-related (C_1) at 25% increases the global weight of "DFD670" from 0.389 to 0.415 (Fig. 7). Increasing management (C_3) by 30% increases the global weight of "DFD670" from 0.389 to 0.409 (Fig. 8). Increasing measurement (C_4) by 35% increases the global weight of "DFD670" from 0.389 to 0.399 (Fig. 9). The weights of "DFD670" have increased under the above three situations. Fig. 10 indicates that increasing human-related (C_2) by 30% reduces the global weight of "DFD670" from 0.389 to 0.377. When human-related (C_2) is increased, the weights of "DFD670" show a downward tendency. When human-related (C_2) is increased, the weights of "DFD670" show a downward tendency. The above situation demonstrates the conclusion of the sensitivity analysis: Constant scientific and technological progress has resulted in highly precise wafer slicing machines and systems. If persons who operate and fix these machines and systems are insufficiently talented or trained, not only will machine and system stability be

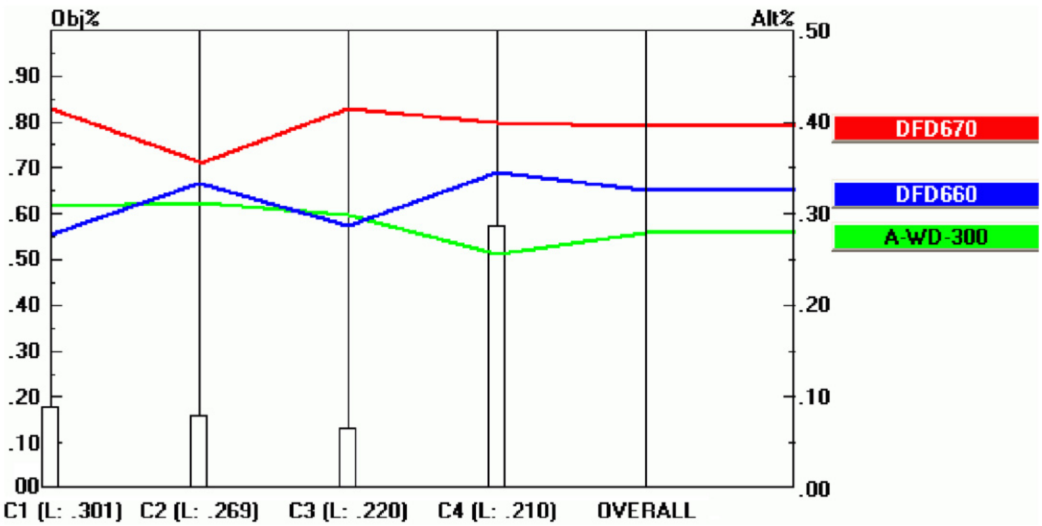

Fig. 9. Performance sensitivity of alternatives when measurement (C_4) is increased by 35%.

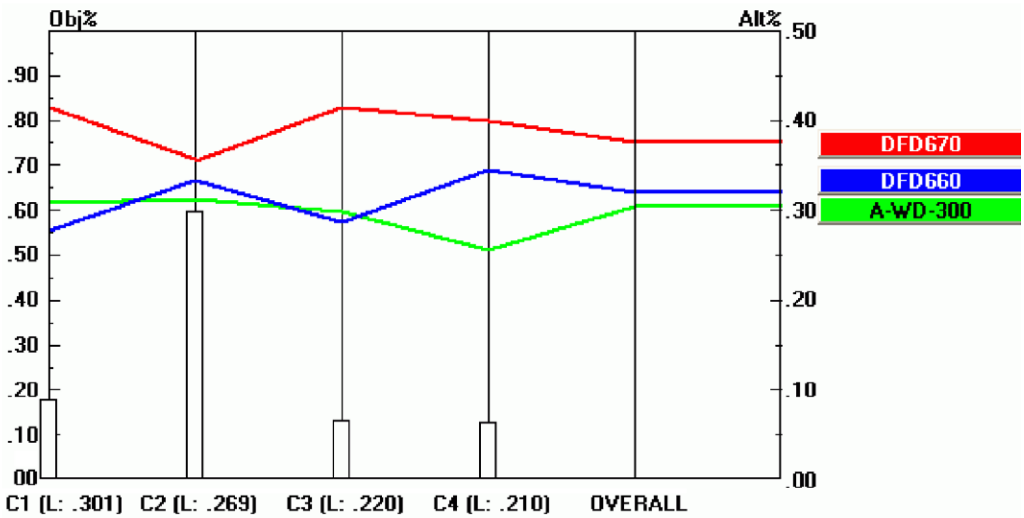

Fig. 10. Performance sensitivity of alternatives when human-related (C_2) is increased by 30%.

negatively impacted, but operating expenses will be increased. Therefore, manager should carefully consider providing professional training.

4. Conclusions

Study of AHP and EWMA shows that the stability of DFD660 and A-WD-300 machines currently is poor, and thus their precision or parameters should be re-examined, and the machines should be closely monitored to avoid bad products influencing the next process. Additionally, this study also shows that the stability of DFD670 machine presently is good, meaning engineers can spend less time examining and monitoring it.

Selecting the samples and then controlling the manufacturing processes is as costly as timely monitoring the quality of the manufacturing processes involved in slicing; however, the former cannot examine tiny parts. This sensitivity analysis can be performed to read the standard of the tolerance limit in which the change influencing the standard reaches a certain level. The results of the sensitivity analysis indicate that human-related mistakes are the main cause to negatively affect the rank of three diamond cutting machines (DFD660, DFD670 and A-WD-300). Therefore, makers should reduce human-related mistakes through education and the inheritance of experience to promote manufacturing process yield of the machines.

After follow-up examination of 133 slices of the silicon wafer, the EWMA control chart can test and verify the mentioned patterns, provide information to policymakers and then perform objective policymaking analyses to strengthen the monitoring of the slicing quality and seek an appropriate opportunity to correct the precision of the machine.

This study can identify the characteristics and criterion that affect the final result of overall quality and manufacturing quality control; therefore, this study could effectively select the best slicing machine, stabilize the monitor direction and enhance the manufacturing quality, thus decreasing the production costs.

Therefore, when the slicing machine is unstable and cannot be monitored, effective control is necessary. This study proposes the use of a multi-criteria technique, namely AHP. AHP can combine quantitative and qualitative factors to handle different groups of actors, and to combine the opinions of many experts. Selecting a silicon wafer slicing manufacturing quality system is extremely complex, and often relies on the subjective assessment of decision makers. Particularly, administrators and engineers in semiconductor manufacturing lack objective decision-making procedures and clearly defined evaluation criteria.

The proposed AHP-based algorithm significantly contributes to the improvement of manufacturing quality in silicon wafer slicing. Specifically, the proposed algorithm can assist semiconductor manufacturers in solving similar multi-criteria problems by offering an objective and systematic method of selecting the optimally performing machine in terms of precision and increasing the quality yield of silicon wafer slicing. Finally, the proposed procedure enables engineers to rapidly adjust a manufacturing system to eliminate problems and to increase slicing quality and process capability.

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