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Analytic network process (ANP) approach for product mix planning in semiconductor fabricator

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Abstract

This paper proposes an application of the analytic network process (ANP) for the selection of product mix for efficient manufacturing in a semiconductor fabricator. In order to evaluate different product mixes, a hierarchical network model based on various factors and the interactions of factors is presented. By incorporating experts' opinion, a priority index can be calculated for each product mix studied, and a performance ranking of product mixes can be generated. The results provide guidance to a fab regarding strategies for accepting orders to maximize the manufacturing efficiency in considering the aspects of product, equipment efficiency and finance. The model can be easily understood and followed by administrators to determine the most efficient product mix for a fab.

Keywords: Analytic network process; Efficiency; Production performance; Product mix; Semiconductor fabricator

1. Introduction

Global competitiveness has become the biggest concern of semiconductor industry. How to increase the overall profit and the return on investment of a company is therefore very essential. The purpose of this paper is aimed at the strategic planning level and attempts to present an effective approach for product mix evaluation that allows for the consideration of various factors and important interactions among factors. The product mix selected can best represent a near-optimal utilization to the factory resources and a highest possible profit attained, and it can be a reference for production planning and order acceptance.

Wafer fabs involve the most complex manufacturing system in the manufacturing world. Its manufacturing process is of high complexity, with several hundreds of processing steps on a single wafer and a flow time of usually more than 1 month. Different product mix only complicates the already-complex system. Depending on the types of products, the process plan of a product can range from very identical to being extremely distinctive, and the requirement of setups may also be different. The greater the difference, the more diverse the loading demand and batch difficulty on the factory. The actual throughput and cycle time under a given product mix thus depend on how badly the fab is bottlenecked, whether the bottleneck is shifted, and how many

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machine setups are needed because of product type conversions.

Many metrics can be applied for evaluating factory productivity. Leachman and Hodges (1996) evaluated semiconductor wafer fabrication plants around the world to quantify manufacturing performance and to establish comparative benchmarks in manufacturing technology, factory operations, organization, and management. The major technical metrics they used to measure manufacturing performance are cycle time per wafer layer, line yield, die yield, stepper productivity, direct labor productivity, total labor productivity and on-time delivery. Although their study provided a comprehensive performance evaluation and identified those practices that underlie top performance, there was no attempt to correlate the interactions of the metrics. There are at least three aspects that are necessary for measuring the overall effectiveness of a factory: production, utilization of assets, and costs (SEMI, 2002). SEMI provided a guideline for definition and calculation of overall factory efficiency (OFE) and other associated factory-level productivity metrics. The document focused on evaluating production; however, utilization of assets and costs were outside of its scope.

Organizing available data and providing a singular metric to compare performances is not an easy task. Chung et al. (2002), however, adopted a good nonlinear programming method called Data Envelopment Analysis (DEA) to deal with multiple inputs and outputs. Without pre-assigning weights, DEA can be used to measure multiple inputs and outputs for product mixes in a semiconductor fabricator, and an efficiency score for producing each product mix relative to other mixes can be obtained. The major advantage of DEA, without pre-assigning weights to any performance measure, can also be its drawback. Managers often have their own opinion on what performance measures are more important than others. In that case, analytic hierarchy process (AHP) and/or analytic network process (ANP) can be a good alternative in evaluating production performance under different product mixes.

While AHP has been a popular research and application tool for multi-attribute decision-making, the ANP technique so far has had only a few applications in literature. A matrix manipulation approach, developed by Saaty and Takizawa (1986), is applied to solve a network, which is very similar to a hierarchy but has dependence among criteria and dependence among alternatives with respect to each criterion. Lee and Kim (2000) used the above-cited ANP approach within a zero-one goal-programming (ZOGP) model to suggest an information system project selection methodology, which can reflect interdependencies among evaluation criteria and candidate projects. Karsak et al. (2002) dealt with product planning in quality function deployment by also using a combined ANP and goal programming approach. Chung et al. (2004) adopted Saaty's matrix manipulation concept and suggested a simplified ANP approach to analyze multiple process inputs and outputs, and with experts' opinion on their priority of importance, to obtain optimal product mixes for semiconductor production. Sarkis (2002) presented a systemic ANP model to evaluate environmental practices and programs in analyzing various projects, technological or business decision alternatives. Momoh and Zhu (1998) proposed an application of AHP and ANP to enhance the selection of generating power units for appropriate price allocation in a competitive power industry. Meade and Sarkis (1999) suggested a decision methodology that applied ANP to evaluate alternatives (e.g. projects) and to help organizations become more agile, with a specific objective of improving the manufacturing business processes. Meade and Presley (2002) used ANP to support the selection of projects in a research and development (R&D) environment.

Suwignjo et al. (2000) and Bititci et al. (2001) constructed an innovative framework and supporting system to let organizations incorporate and map performance measures in a hierarchical way. The quantitative model for performance measurement system (QMPMS) relies on AHP to quantify both tangible and intangible factors for performance. Bititci et al. further applied the QMPMS for manufacturing strategy evaluation and management in a dynamic environment. Sarkis (2002) revisited the above works and applied ANP to the QMPMS process. Through the utilization of the supermatrix approach, the combined effects of factors on organizational performance measures can be quantified, and the dynamic nature of strategic decisions can be evaluated.

Saaty suggested the use of AHP to solve the problem of independence on criteria and alternatives and the use of ANP to solve the problem of dependence among criteria and/or alternatives (Saaty, 1996). The metrics for measuring manufacturing performance, such as production throughput, cycle time, equipment utilization and WIP are highly interrelated. While some metrics are positively dependent, others may be negatively dependent. As a result, ANP is adopted in this research for determining the production performance of various product mixes.

Semiconductor companies as well as other industries need good problem solving methods that can be used in real practice. While ANP provides a good quantitative and qualitative tool to assist administrators, they may feel threatened by its complexity if they have no experience or a good understanding of the method. This paper can provide a good prototype for the users to conceptualize the process and to follow the procedure in the determination of a suitable product mix in manufacturing.

This paper is organized as follows. Section 2 discusses the process parameters selected for evaluation, and a multi-attribute selection framework represented as an ANP model is presented. Section 3 describes the system environment for simulation. Section 4 applies ANP to the evaluation of the efficiency under different product mixes. Some conclusion remarks are made in the last section, while the appendix briefly reviews the decision making tool ANP.

2. Process parameters for evaluation

Different product mix has a different impact to the production performance, and production performance is a result of the interaction among equipment set availability, control rules and loading condition, just to name a few. In addition, there is no optimum production performance since different people are interested in different performance indicators. For example, finance people may be interested in the final profit a fab can make, while industrial engineers want to generate the maximum throughput and maintain production smoothness. Furthermore, some performance indicators are positively related, but others may be counter-active. Therefore, based on the performance indicator selected, the performance evaluation under a specific product mix will be different. Which performance measures should be considered and the importance of each measure, are essential in the analysis. Based on the ANP method, senior managers and experts from the Science-Based Industrial Park in Taiwan are interviewed first to decide the major criteria and the subsequent detailed criteria for evaluating performance under different product mixes. The hierarchical network structure, which composes of three major criteria and numerous detailed criteria, is established as shown in Fig. 1. Criteria are assumed to interrelate to each other; in consequence, detailed criteria are all interrelated even if they have different upper level criteria.

The three major criteria and detailed criteria for measuring manufacturing performance of a semiconductor fab are defined as follows:

(1) *Product*: How products are manufactured in a fab.
  - *WIP* gives the number of lots that have been released into the wafer fab but have not yet been finished processing through all of their manufacturing steps.
  - *Throughput* (TP) shows the number of lots that pass through the final operation step in a period.
  - *Total layers* (TL) accounts the number of layers the bottleneck resource processed in a period of time.
  - *Total cycle time* (CT) measures the duration of time, expressed in hours, consumed by a unit of production from the time of release into the fab until time of exit from the fab. It is a weighted average cycle time, where the weights are the ratio of product mix.

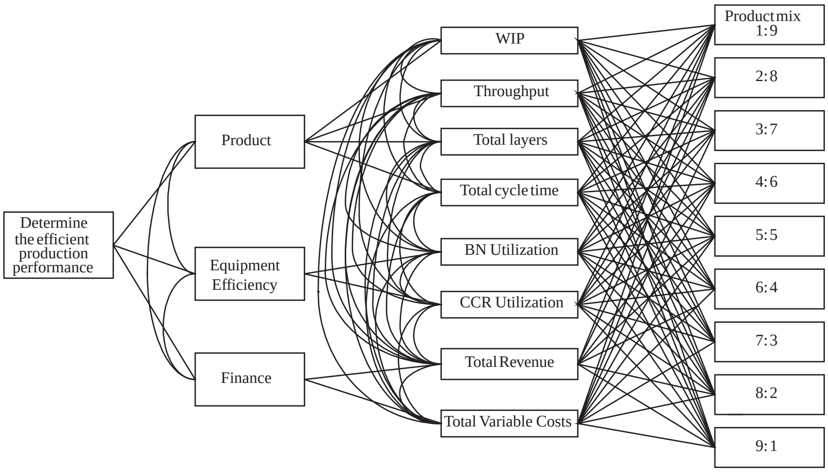

Fig. 1. The network analyzed in this paper.

(2) *Equipment efficiency*: How effective the equipment is used in manufacturing, a measure of equipment performance.
  - *Bottleneck utilization* (BU) shows average utilization rate of the bottleneck in the system for a period of time. Since the throughput of the entire manufacturing system is determined by the bottleneck workstation, BN utilization should be as high as possible.
  - *Capacity constrained resource* (*CCR*) *utilization* (CU) shows average utilization rate of the CCR in the system for a period of time. Although CCR is not a bottleneck, it also has a substantially high utilization rate. When CCR utilization rate is too high, there is a chance of bottleneck shifting.

(3) *Finance*: The amount of money a wafer fab can make or needs to spend in the manufacturing process. All finished products are assumed sold. Product price is determined by the market according to its product type. Most manufacturing costs of a semiconductor fabricator are fixed; that is, no matter how many products are produced, the operating costs are not varied much.
  - *Total revenue* (TR) is obtained by summing up revenue of each product type, while revenue of a product type is calculated by multiplying the price of the product type with its throughput and the price for a product is set by its product type and the number of layers that product goes through.
  - *Variable costs* (VC) include two major parts: total variable manufacturing costs and total holding costs. Direct material cost, the cost of raw wafers, is the primary part of total variable manufacturing costs. Other variable manufacturing costs include indirect material cost and is varied according to the manufacturing level. The holding cost is the time cost of carrying WIP in the manufacturing system.

Senior managers of several semiconductor manufacturing companies in Science-Based Industrial Park in Taiwan and academic experts were involved in evaluating the criteria and subcriteria and gave pairwise comparison values.

3. System input and simulation

The simulation model for this study has been developed using data from an existing wafer fabrication factory located on the Science-Based Industrial Park in Taiwan. To simplify the complexity of the environment for our analysis,

Table 1
Simulation results

Product mix	WIP (lots)	TP (lots)	T L(#)	CT (h)	BU (%)	CU (%)	VC ($)
I: Mix (1:9)	249.05	540	11,124	309.92	0.99	0.9	3,679,743
II: Mix (2:8)	248.9	548	11,070	305.2	0.99	0.87	3,667,558
III: Mix (3:7)	248.95	556	11,009	300.85	0.99	0.85	3,653,426
IV: Mix (4:6)	249.09	562	10,903	296.76	0.99	0.82	3,624,447
V: Mix (5:5)	249.27	570	10,830	292.85	0.99	0.79	3,606,663
VI: Mix (6:4)	249.45	580	10,788	288.99	0.99	0.76	3,599,343
VII: Mix (7:3)	249.61	588	10,702	285.23	0.99	0.76	3,577,421
VIII: Mix (8:2)	249.74	596	10,609	281.6	0.99	0.7	3,553,551
IX: Mix (9:1)	252.18	608	10,579	278.78	0.99	0.67	3,551,096

the simulation model is built under several assumptions. The fab consists of 83 workstations (W1–W83), and each workstation consists of a given number of identical machines operated in parallel. There are a total of 235 machines, which can be grouped into two types: batch and serial. The machines are subject to downtimes due to preventive maintenance and failures. W46, a stepper in the photolithography area, is the bottleneck, and W38, with a high utilization rate that is next to that of bottleneck, is the CCR. The strategy of manufacturing is to maximize the utilization of bottleneck. Two types of products, L and M, are manufactured, and both products are normal; that is, there is only one priority level. Product L is a logic product, while product M is a memory product. Each product type follows a distinct route. Product L requires 276 operations and passes through the bottleneck 16 times. That is, 17 layers are processed. Product M requires 330 operations and passes through the bottleneck 21 times (22 layers processed).

The releasing batch size is set to six lots for effective use of many workstations, which have a maximum batch size (MBS) of six lots. Lots with different product types cannot be processed simultaneously. Wafer lots are released under CONWIP, a fixed work-in-process (WIP) policy. The dispatching rule is first-in, first-out (FIFO). Product price is generally determined by the supply and demand of the market according to the product type and the number of layers the product needs to be processed. Because product price can vary tremendously in different time horizons, several cases of price variation are analyzed in this paper and will be covered in detail in the next section. Direct material cost is assumed to be $100 per wafer. Indirect material cost, such as photo-resist, special gas, chemical and quartz, is set to $7.5 per layer for product L and $8 per layer for product M. A holding cost is considered for the WIP at an annual rate of 10%. Because CONWIP is adopted, WIP level is consistent throughout the period. Material is the major variable cost of a product, and the holding cost of material of the WIP will be calculated as: Total material cost of the WIP × holding rate for the period.

The simulation program used in this research is EM-PLANT (Tecnomatix, 2001). The planning horizon in the simulation is set to 168 working days. Each working day consists of 24 working hours. The first 84 days are a warm-up period; hence, only results belonging to the next 84 days are collected. The simulation model is run 15 times to get adequate statistical results under each product mix. The data obtained from running simulation for each product mix (represented by I–IX) with manufacturing ratio of L to M is shown in Table 1.

4. ANP for product mix determination

In this section, an ANP approach is used. A total of nine experts contributed their professional experience to identify criteria and subcriteria that influence the decision and constructed the network of determining the efficient manufacturing performance as already shown in Fig. 4. Six of them are senior managers of production planning and finance departments from three internationally well-known semiconductor manufacturing companies in Science-Based Industrial Park in Taiwan, and the other three are scholars in production management from three universities in Taiwan. Here we take into consideration the interrelationship among criteria with respect to the goal and also the interrelationship among detailed criteria with respect to an upper level criterion (i.e., *product*, *equipment efficiency* and *finance*).

The first step is to construct the comparison matrices at each component for pairwise comparison of the factors inside the component. The Delphi method was performed to obtain a consensus among the people who were involved (Forgarty et al., 1989). The Delphi method consisted of a series of repeated interrogations through questionnaires of a group of experts and managers whose judgments were of interest in order to arrive at a group position regarding an issue. After the initial interrogation of each individual, each subsequent interrogation was accompanied by providing information of preceding round of replies. Individuals were encouraged to reconsider and change their previous reply with the consideration of the replies of other members of the group. The group position was finally determined after four rounds.

There are a total of 15 pairwise comparisons. The goal and criteria for each pairwise comparison are listed in Appendix B, and the details are explained as follows. First, the importance of each decision criteria with respect to achieving the overall objective, the efficient production performance, is determined. The question, “which criteria should be emphasized more in determining efficient manufacturing, and how much more?” was asked, and a nine-point scale was used to do the pairwise comparison. An example of pairwise comparison is shown in Table 2, and the comparison matrix for comparing the criteria (*product*, *equipment efficiency* and *finance*) in terms of their contribution to achieving the overall objective is shown in Table 3.

The priorities for the criteria, w_{21}, can be obtained by the procedure stated in Step 2 in the previous section and is

$$w_{21} = \begin{array}{c} P \\ E \\ F \end{array} \begin{bmatrix} 0.258 \\ 0.105 \\ 0.637 \end{bmatrix}. \qquad (1)$$

The eigenvector shows the priority of the three criteria. In the opinion of the senior managers and experts, *finance*, with a weight of 0.637, is the major factor in determining the efficiency of manufacturing performance simply because profitability is the ultimate goal of a company. *Product* and *equipment efficiency* rank the second and the

Table 3
Comparison matrix for the criteria

	Product	Equipment efficiency	Finance
Product	1	3	1/3
Equipment efficiency	1/3	1	1/5
Finance	3	5	1

Table 2
Pairwise comparison

In order to achieve the most efficient manufacturing performance, which criteria should be emphasized more?																		
	Absolute		Very strong		Strong		Weak		Equal		Weak		Strong		Very strong		Absolute	
	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	1:2	1:3	1:4	1:5	1:6	1:7	1:8	1:9	
Product							X											Equipment efficiency
Product											X							Finance
Equipment efficiency													X					Finance

third with weights of 0.258 and 0.105. The consistency of this combination of values in the matrix is also checked to make sure that the interviewees do not make inconsistent judgment.

Assume there is no interdependence among detailed criteria, which detailed criteria should be emphasized more in determining their respective upper level criterion? The comparison matrices of detailed criteria in accordance to their respective upper level criteria (*product*, *equipment*, *finance*) and their eigenvectors are obtained. The comparison matrix and eigenvector for *product* are shown in Table 4. Pairwise comparison among its detailed criteria, *WIP*, *throughput*, *total layers* and *cycle time*, shows that *total layers*, the total number of layers the bottleneck can process in a period of time, is the most important factor with a weight of 0.499, followed by *throughput* with a weight of 0.284. For the criteria *equipment efficiency*, *bottleneck utilization*, with a weight of 0.9, is the main focus since it governs the total output of the manufacturing system. For the criteria *finance*, *total revenue*, with a weight of 0.857, is relatively much more important than *variable costs*. In the group's judgment, fixed cost accounts for the majority part of the total manufacturing costs, and variable costs under different manufacturing environments generally do not vary too much either. Revenue, on the other hand, is the indication of the success of a company and thus has a much higher contribution.

The eigenvectors for *product* ($w_{32(P)}$), *equipment efficiency* ($w_{32(E)}$) and *finance* ($w_{32(F)}$) are organized into a matrix, $\mathbf{W}_{32}$, that represents the relative importance of detailed criteria with respect to their upper level criteria.

$$\mathbf{W}_{32} = \begin{array}{c} \\ \text{WIP} \\ \text{TP} \\ \text{TL} \\ \text{CT} \\ \text{BU} \\ \text{CU} \\ \text{TR} \\ \text{VC} \end{array} \begin{array}{c} \begin{array}{ccc} P & E & F \end{array} \\ \begin{bmatrix} 0.134 & 0 & 0 \\ 0.284 & 0 & 0 \\ 0.499 & 0 & 0 \\ 0.083 & 0 & 0 \\ 0 & 0.900 & 0 \\ 0 & 0.100 & 0 \\ 0 & 0 & 0.857 \\ 0 & 0 & 0.143 \end{bmatrix} \end{array}. \tag{2}$$

As stated in the previous section, product price fluctuates in time and is determined by the market condition at the time of order commitment. Prices of different product types can also be very different. For instance, even though the operations of logic I.C. are less than memory I.C., it may require a special recipe and its process can be more complex. In addition, the quantity of logic I.C. demanded by the clients is usually smaller than that of memory I.C. Therefore, the price of logic I.C. is generally higher than memory I.C. Because *finance* is the major concern of the people interviewed, and *revenue* under *finance* is much more important than the other factor, *variable costs*, we will evaluate several cases of different product prices under our simulation model.

When the price of logic I.C. (PL) is higher than or equal to that of memory I.C. (P_{M}), total revenue has an increasing trend as the ratio of product L increases. This is because product L requires less of operations than product M, and the total throughput increases as a higher ratio of product L is manufactured. The dual effect of a higher price of P_{L} and a higher throughput increases the total revenue as more product L is manufactured. On the other hand, when P_{L} is lower than P_{M}, total revenue may increase, decrease, or indeterminate from manufacturing product mix (1:9) to (9:1). As just mentioned, the total throughput increases as a higher ratio of product L is manufactured. The revenue generated from a higher throughput of product L with a lower price and a lower throughput of product M with a higher price, thus, is a result of counter-effects. The trend of total revenue will be

Table 4
Comparison matrix and eigenvector for *product*

Product	WIP	TP	TL	CT	Relative importance weights (eigenvector, $w_{32(P)}$)
WIP	1	1/3	1/3	2	0.134
TP	3	1	1/3	4	0.284
TL	3	3	1	4	0.499
CT	1/4	1/4	1/4	1	0.083

CR = 0.07.

determined by the difference between P_L and P_M. For instance, if P_L is $US 100 lower than P_M, as more product L is manufactured, total revenue decreases when P_L is less than or equal to $400 and increases when P_L is more than or equal to $900. However, when P_L is between $450 and $850, total revenue may either increase or decrease. Table 5 and Fig. 2 show some results of total revenue when P_L is $100 lower than P_M. Fig. 3 shows the total revenue when P_L is $150 lower than P_M. Total revenue decreases as more product L is manufactured when P_L is less than or equal to $700, and increases when P_L is more than or equal to $1350. In Fig. 4, total revenues of different product mixes when P_L is $200 lower than P_M are analyzed. As more product L is manufactured, total revenue decreases when P_L is less than or equal to $900, and increases when P_L is more than or equal to $1800. Note that the results of total revenue of $P_M - P_L = \$200$ are exactly double of the results of $P_M - P_L = \$100$. For example, when $P_L = \$500$ and $P_M = \$600$, Mix (1:9) has a total revenue of $7,965,000. When $P_L = \$1000$ and $P_M = \$1200$, Mix (1:9) has a total revenue of $15,930,000; both prices and total revenue are a double of the previous case. The total revenue trend of $P_L = \$1000$ and $P_M = \$1200$ is exactly the same as that of $P_L = \$500$ and $P_M = \$600$, only that the amount is double. Same conclusions can be made for $P_M - P_L = \$300$ and $P_M - P_L = \$150$, just to name a few.

Following are four representative cases that will be used for our ANP analysis, and the total revenues of different product mixes under the four cases are shown in Table 6.

Case I: Price of logic I.C. (P_L) is greater than or equal to that of memory I.C. (P_M). If we let P_L be $US 1200 and P_M be $US 1000, the total revenues has an increasing trend as the ratio of product L increases.

Table 5
Total revenues of different product mixes when $P_M - P_L = \$100$ (US$)

Mix (L:M)	$P_L = \$450$, $P_M = \$550$	$P_L = \$500$, $P_M = \$600$	$P_L = \$600$, $P_M = \$700$	$P_L = \$850$, $P_M = \$950$	$P_L = \$900$, $P_M = \$1000$
Mix(1:9)	7,290,000	7,965,000	9,315,000	12,690,000	13,365,000
Mix(2:8)	7,261,000	7,946,000	9,316,000	12,741,000	13,426,000
Mix(3:7)	7,228,000	7,923,000	9,313,000	12,788,000	13,483,000
Mix(4:6)	7,165,500	7,868,000	9,273,000	12,785,500	13,488,000
Mix(5:5)	7,125,000	7,837,500	9,262,500	12,825,000	13,537,500
Mix(6:4)	7,105,000	7,830,000	9,280,000	12,905,000	13,630,000
Mix(7:3)	7,056,000	7,791,000	9,261,000	12,936,000	13,671,000
Mix(8:2)	7,003,000	7,748,000	9,238,000	12,963,000	13,708,000
Mix(9:1)	6,992,000	7,752,000	9,272,000	13,072,000	13,832,000
Changes of revenue as product L increases	Decrease	Decrease, then increase	Increase and decrease alternately	Increase, decrease and increase	Increase

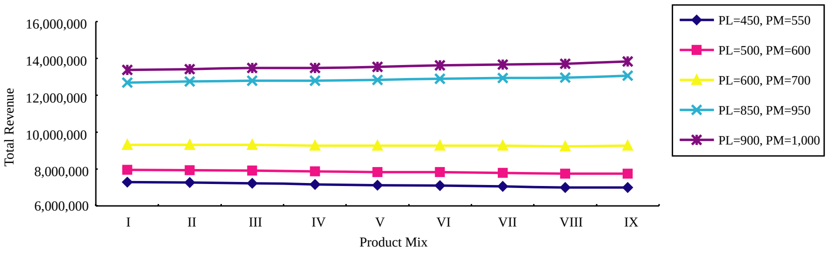

Fig. 2. Total revenues of different product mixes when $P_M - P_L = \$100$.

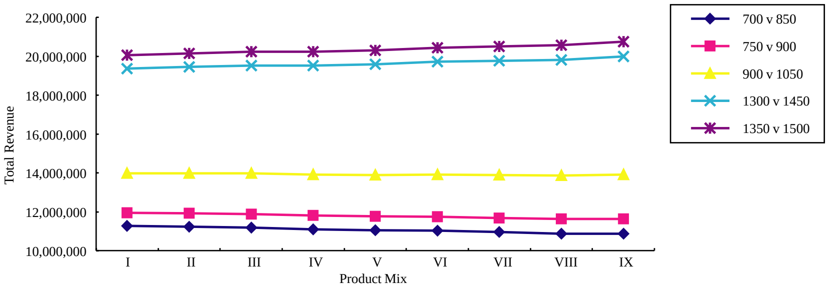

Fig. 3. Total revenues of different product mixes when $P_M - P_L = \$150$.

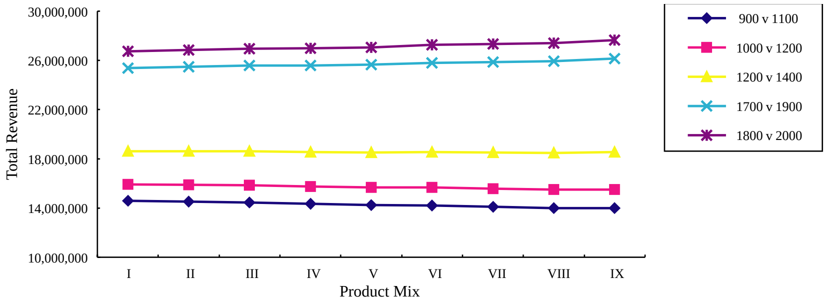

Fig. 4. Total revenues of different product mixes when $P_M - P_L = \$200$.

Table 6
Total revenues of different product mixes under the four cases ($US)

Product mix (L:M)	Case I: $P_L = \$1200$ and $P_M = \$1000$	Case II: $P_L = \$800$ and $P_M = \$1000$	Case III: $P_L = \$1200$ and $P_M = \$1400$	Case IV: $P_L = \$1900$ and $P_M = \$2100$
I: Mix (1:9)	13,770,000	13,230,000	18,630,000	28,080,000
II: Mix (2:8)	14,248,000	13,152,000	18,632,000	28,222,000
III: Mix (3:7)	14,734,000	13,066,000	18,626,000	28,356,000
IV: Mix (4:6)	15,174,000	12,926,000	18,546,000	28,381,000
V: Mix (5:5)	15,675,000	12,825,000	18,525,000	28,500,000
VI: Mix (6:4)	16,240,000	12,760,000	18,560,000	28,710,000
VII: Mix (7:3)	16,758,000	12,642,000	18,522,000	28,812,000
VIII: Mix (8:2)	17,284,000	12,516,000	18,476,000	28,906,000
IX: Mix (9:1)	17,936,000	12,464,000	18,544,000	29,184,000

Case II: Price of logic I.C. (P_L) is lower than that of memory I.C. (P_M). Assume $P_M - P_L = \$200$, and $P_L = \$800$ and $P_M = \$1000$. Total revenue has a decreasing trend as the ratio of product L increases.

Case III: Price of logic I.C. (P_L) is lower than that of memory I.C. (P_M). Assume $P_M - P_L = \$200$, and $P_L = \$1200$ and $P_M = \$1400$. Total revenue fluctuates as the ratio of product L increases.

Case IV: Price of logic I.C. (P_L) is lower than that of memory I.C. (P_M). Assume $P_M - P_L = \$200$, and $P_L = \$1900$ and $P_M = \$2100$. Total revenue has an increasing trend as the ratio of product L increases.

Since there is no interdependence among alternatives (product mix), the alternatives are compared with respect to each detailed criterion yielding the column eigenvectors regarding each detailed criterion. The simulation data from Table 1 and the different cases of total revenue from Table 6 are used here to form the comparison matrices of alternatives (product mixes) with respect to each detailed criteria (*WIP*, *throughput*, etc.). The reason of not using the opinion of senior managers and experts in identifying the relative score of the alternatives with respect to each of the detailed criteria is because simulation data, which indicate the manufacturing performance of a fab under different product mixes, are objective measures to reflect the efficiency of manufacturing. Because the unit of measurement of simulation data is various and can range from number of layers to percentage and to dollars, these quantitative data need to be transformed into values between zero to one. The concept of utility function is adopted to obtain a utility index and to show the relative performance of a factor under each product mix. By assigning values of zero and one to the worst and best outcomes, the general formula of a utility linear function of detailed criteria m is as follows (Clemen, 1996):

$$u_m(x) = \frac{X - X_m^-}{X_m^+ - X_m^-}, \tag{3}$$

where X_m^+ is the best value of detailed criteria m, X_m^- the worst value of detailed criteria m, X the value of detailed criteria m under a certain product mix.

In this paper, numerous simulations are run to collect sufficient data, and X_m^+ and X_m^- are the values that are suitable to be the two extreme levels of performance. For some detailed criteria (*throughput*, *total layers*, *BN utilization*, *CCR utilization* and *total revenue*), their values are preferred to be as great as possible, and thus the best factors are those with the largest values, and vice versa. On the other hand, for other detailed criteria (*WIP*, *total cycle time* and *variable costs*), we prefer their values to be small, and therefore the best ones have the smallest values. The simulation results in Table 2 and total revenue data from Table 6 are transformed into utility indices as shown in Table 7.

The utility indices are then transformed into weights by dividing each utility index to the total value of the column so that each column sums up to one. Table 8 shows the matrix, $W_{43(1)}$, that indicates the utility weights of alternatives with respect to each detailed criterion for Case I. For other cases, the matrix can be obtained by replacing the column of total revenue (TR) by the column of the specific case listed in Table 9.

The inner dependence among the criteria is determined through analyzing the impact of each criterion on other criteria by using pairwise comparisons. We ask questions such as "What is the relative importance of *equipment efficiency* when compared to *finance* on controlling *product*?" The result is 2 as denoted in Table 10, which shows the inner dependence matrix of criteria with respect to *product*. The dependencies among criteria are depicted in Fig. 5. The resulting eigenvectors obtained from pairwise comparisons formed matrix, W_{22}, and are shown in Table 11. Note that zeros are assigned to the eigenvector weights of criteria that are independent.

The inner dependence among the detailed criteria is analyzed next. A similar procedure as for the inner dependence among criteria is adopted here, except that correlation analysis of the simulation results is performed first and the results are used as a reference for the experts. A possible question is as follows: "What is the relative importance of *cycle time* (CT) when compared to *bottleneck utilization* (BU) on controlling *throughput* (TP)?" The answer is 2 as shown in Table 12.

The schematic representation of the relationship among detailed criteria is presented in Fig. 6. The relative importance weights of the inner dependence among detailed criteria are represented by W_{33} in Table 13.

A supermatrix allows for the resolution of the effects of interdependence between the elements of the system. It is a partitioned matrix, where each submatrix is composed of the vectors obtained from the pairwise comparison. As discussed in the appendix and shown by the dotted bracket in Fig. 10, the supermatrix in this paper covers all the components in the network. The generalized form of the supermatrix is shown in Fig. 7.

The supermatrix for Case I, inserted with respective vectors and matrices obtained before, is shown in Table 14. Because the supermatrix includes interactions between clusters, e.g. there is

Table 7
Utility index of each detailed criteria under different product mix

Alternative	WIP	TP	TL	CT	BU	CU	VC
I	0.547	0.267	0.562	0.002	1.000	1.000	0.101
II	0.555	0.320	0.535	0.120	1.000	0.900	0.162
III	0.553	0.373	0.505	0.229	1.000	0.833	0.233
IV	0.546	0.413	0.452	0.331	1.000	0.733	0.378
V	0.537	0.467	0.415	0.429	1.000	0.633	0.467
VI	0.528	0.533	0.394	0.525	1.000	0.533	0.503
VII	0.519	0.587	0.351	0.619	1.000	0.533	0.613
VIII	0.513	0.640	0.305	0.710	1.000	0.333	0.732
IX	0.391	0.720	0.290	0.781	1.000	0.233	0.745
Sum of column	4.688	4.320	3.807	3.746	9.000	5.733	3.934

Alternative	TR (Case I)	TR (Case II)	TR (Case III)	TR (Case IV)
I	0.154	0.615	0.630	0.040
II	0.250	0.576	0.632	0.111
III	0.347	0.533	0.626	0.178
IV	0.435	0.463	0.546	0.191
V	0.535	0.413	0.525	0.250
VI	0.648	0.380	0.560	0.355
VII	0.752	0.321	0.522	0.406
VIII	0.857	0.258	0.476	0.453
IX	0.987	0.232	0.544	0.592
Sum of column	4.964	3.791	5.061	2.576

Table 8
Utility weights of alternatives with respect to each detailed criterion for Case I, $\mathbf{W}_{43(\mathrm{I})}$

Alternative	WIP	TP	TL	CT	BU	CU	TR	VC
I	0.117	0.062	0.148	0.001	0.111	0.174	0.031	0.026
II	0.118	0.074	0.141	0.032	0.111	0.157	0.050	0.041
III	0.118	0.086	0.133	0.061	0.111	0.145	0.070	0.059
IV	0.116	0.096	0.119	0.088	0.111	0.128	0.088	0.096
V	0.114	0.108	0.109	0.114	0.111	0.110	0.108	0.119
VI	0.113	0.123	0.103	0.140	0.111	0.093	0.131	0.128
VII	0.111	0.136	0.092	0.165	0.111	0.093	0.151	0.156
VIII	0.109	0.148	0.080	0.190	0.111	0.058	0.173	0.186
IX	0.083	0.167	0.076	0.208	0.111	0.041	0.199	0.189

inner dependence among criteria and among detailed criteria, not each of the columns sums to one. A weighted supermatrix for Case I is transformed first to be stochastic as shown by $\mathbf{M}_{\mathbf{I}}^{\mathrm{W}}$ in Table 15. The weighted supermatrix is then raised to limiting powers to be $\mathbf{M}_{\mathbf{I}}^{2k+1}$ (where k is an arbitrarily large number) to capture all the interactions and to obtain a steady-state outcome. In Case I, convergence is reached at $\mathbf{M}_{\mathbf{I}}^{33}$, and the limit supermatrix, which shows the long-term stable weighted values, is shown in Table 16.

The overall priorities for the alternatives (product mixes) for Case I is given by the bottom left corner, the (4,1) block, of $\mathbf{M}_{\mathbf{I}}^{33}$. The alternative with the largest priority index should be the one selected. Alternative IX (product mix (9:1)), with a relative importance value of 0.1639, is the most efficient manufacturing product mix, followed by alternative VIII (product mix (8:2)) with a value of 0.1502. The ranking of the product mixes for Case I is exactly the descending order from alternative IX to I, that is, from product mix (9:1) to (1:9). This implies that product L is highly recommended for manufacturing. The outcome is not hard to explain from the simulation results and the matrices obtained before. In the group's opinion, *finance*, with a weight of 0.637, is much more important than other criteria. In addition, under criteria *finance*, *total revenue* is a lot more important than *variable costs*. *Total revenue* has an increasing trend as a higher ratio of product L, which has a higher price than M, is produced. In addition, factors such as *throughput*, *cycle time* and *variable costs*, all favor in manufacturing product L.

The overall priorities of the alternatives under the other three cases are shown in Table 17. The ranking of the product mixes for Case II is in the order as the ratio of product L increases until meeting alternative IX, which has a higher overall priority than alternative VIII. For Case IV, the efficiency of the product mixes increases from alternative I–IX. Case III is a good representative case which shows that *total revenue* is not the only determinant of the final ranking of product mixes. Table 18 shows the ranking of alternatives by total revenue versus by the ANP. The alternative with the highest total revenue is alternative II, followed by alternative I and III. However, alternative IX ranks the first under the ANP analysis, and the ranking is in the order from alternative IX–I. This indicates that the ANP ranking is not solely influenced by the *total revenue*, but also by the other factors and the interactions among the factors.

Table 9
Utility weight of alternatives with respect to *total revenue* (TR) for Cases II, III and IV

	TR (Case II)	TR (Case III)	TR (Case IV)
I	0.162	0.124	0.016
II	0.152	0.125	0.043
III	0.141	0.124	0.069
IV	0.122	0.108	0.074
V	0.109	0.104	0.097
VI	0.100	0.111	0.138
VII	0.085	0.103	0.158
VIII	0.068	0.094	0.176
IX	0.061	0.107	0.230

5. Conclusions

The ANP is presented in this paper as a valuable method to support the selection of product mix that is efficient for a wafer fab to manufacture.

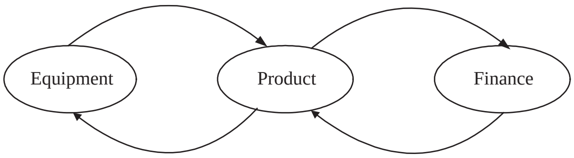

Fig. 5. Inner dependence among criteria.

Table 11
Inner dependence matrix of criteria, $\mathbf{W}_{22}$

	Product	Equipment efficiency	Finance
Product	0.529	0.25	0.100
Equipment efficiency	0.309	0.75	0
Finance	0.162	0	0.900

Table 10
Inner dependence matrix of criteria with respect to *product*

Product	Product	Equipment efficiency	Finance	Relative importance weights (eigenvector)
Product	1	2	3	0.529
Equipment efficiency	1/2	1	2	0.309
Finance	1/3	1/2	1	0.162

Table 12
Inner dependence matrix of detailed criteria with respect to *throughput*

TP	WP	TP	TL	CT	BU	CU	TR	VC	Relative importance weights (eigenvector)
WP	1	1/2	0	1	2	0	1/2	0	0.168
TP	2	1	0	2	3	0	2	0	0.3358
TL	0	0	0	0	0	0	0	0	0
CT	1	1/2	0	1	2	0	1	0	0.1848
BU	1/2	1/3	0	1/2	1	0	1/2	0	0.0958
CU	0	0	0	0	0	0	0	0	0
TR	2	1/2	0	1	2	0	1	0	0.218
VC	0	0	0	0	0	0	0	0	0

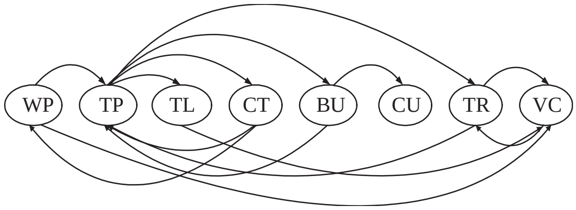

Fig. 6. Inner dependence among detailed criteria.

Table 13
Inner dependence matrix of detailed criteria, $\mathbf{W}_{33}$

	WIP	TP	TL	CT	BU	CU	TR	VC
WIP	0.667	0.168	0	0	0	0	0	0.085
TP	0	0.335	0.333	0.333	0.333	0	0.308	0
TL	0	0	0.667	0	0	0	0	0.327
CT	0.333	0.184	0	0.667	0	0	0	0
BU	0	0.095	0	0	0.667	0.333	0	0
CU	0	0	0	0	0	0.667	0	0
TR	0	0.218	0	0	0	0	0.615	0.196
VC	0	0	0	0	0	0	0.077	0.392

$$\begin{array}{l|cccc|}
 & \text{Goal} & \text{Criteria} & \text{Detailed Criteria} & \text{Alternatives} \\
\hline
\text{Goal} & \mathbf{I} & & & \\
\text{Criteria} & w_{21} & \mathbf{W}_{22} & & \\
\text{Detailed Criteria} & & \mathbf{W}_{32} & \mathbf{W}_{33} & \\
\text{Alternatives} & & & \mathbf{W}_{34} & \mathbf{I}
\end{array}$$

Fig. 7. Generalized supermatrix.

The relative prices of products affect the total revenue trend under different product mixes, and the ANP can be applied to determine the efficiency of product mix when product prices change. Because profitability is the key to success for an enterprise, relative prices of products and the total revenues generated from different product mixes can often determine the desirable product mix. This is shown by the trend of the ranking of alternatives under most cases studied in this paper. However, there are times when the ranking of alternatives is not exactly the same as the ranking of total revenue of alternatives. This means that factors other than total revenue do have impact on the efficiency evaluation of product mixes. In this paper, the approach adopts ANP to deal with interrelated factors and provides users with procedures to be followed for the determination of a suitable product mix for wafer fabrication.

When product mix is predictable or when all products use each facility equally, an overall production forecast is sufficient to determine equipment requirements. However, when various products follow distinct routes and have different loadings on machines, any deviation from the product mix target can make the workstation utilizations time-varying over the planning horizon. The time-varying utilizations will in turn cause time-varying cycle times. How product mix should be set in a longer term will be our future research direction. In addition, due to the intensive competition in semiconductor industry, a variety of products are usually required to be

Table 14
The supermatrix for Case I, $\mathbf{M}_{\mathbf{I}}$

	Goal	Product	Equipment	Finance	WP	TP	TL	CT	BU	CU	TR	VC	I	II	III	IV	V	VI	VII	VIII	IX
Goal	1																				
Product	0.258	0.529	0.25	0.100																	
Equipment	0.105	0.309	0.75	0																	
Finance	0.637	0.162	0	0.900																	
WP		0.134	0	0	0.667	0.168	0	0	0	0	0	0.085									
TP		0.284	0	0	0	0.335	0.333	0.333	0.333	0	0.308	0									
TL		0.499	0	0	0	0	0.667	0	0	0	0	0.327									
CT		0.083	0	0	0.333	0.184	0	0.667	0	0	0	0									
BU		0	0.9	0	0	0.095	0	0	0.667	0.333	0	0									
CU		0	0.1	0	0	0	0	0	0	0.667	0	0									
TR		0	0	0.857	0	0.218	0	0	0	0	0.615	0.196									
VC		0	0	0.143	0	0	0	0	0	0	0.077	0.392									
I					0.117	0.062	0.148	0.001	0.111	0.174	0.031	0.026	1								
II					0.118	0.074	0.141	0.032	0.111	0.157	0.05	0.041		1							
III					0.118	0.086	0.133	0.061	0.111	0.145	0.07	0.059			1						
IV					0.116	0.096	0.119	0.088	0.111	0.128	0.088	0.096				1					
V					0.114	0.108	0.109	0.114	0.111	0.11	0.108	0.119					1				
VI					0.113	0.123	0.103	0.14	0.111	0.093	0.131	0.128						1			
VII					0.111	0.136	0.092	0.165	0.111	0.093	0.151	0.156							1		
VIII					0.109	0.148	0.08	0.19	0.111	0.058	0.173	0.186								1	
IX					0.083	0.167	0.076	0.208	0.111	0.041	0.199	0.189									1

Table 15
The weighted supermatrix for Case I, $\mathbf{M}_{\mathbf{I}}^{\mathrm{W}}$

	Goal	Product	Equipment	Finance	WP	TP	TL	CT	BU	CU	TR	VC	I	II	III	IV	V	VI	VII	VIII	IX
Goal	0.5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Product	0.1290	0.2645	0.1250	0.0500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Equipment	0.0525	0.1545	0.3750	0.0000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Finance	0.3185	0.0810	0.0000	0.4500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WP	0	0.0670	0.0000	0.0000	0.3334	0.0838	0	0	0	0	0	0.0425	0	0	0	0	0	0	0	0	0
TP	0	0.1420	0.0000	0.0000	0	0.1676	0.1667	0.1667	0.1667	0	0.1539	0	0	0	0	0	0	0	0	0	0
TL	0	0.2495	0.0000	0.0000	0	0.0000	0.3334	0	0	0	0	0.1634	0	0	0	0	0	0	0	0	0
CT	0	0.0415	0.0000	0.0000	0.1667	0.0922	0	0.3334	0	0	0	0	0	0	0	0	0	0	0	0	0
BU	0	0.0000	0.4500	0.0000	0	0.0475	0	0	0.3334	0.1667	0	0	0	0	0	0	0	0	0	0	0
CU	0	0.0000	0.0500	0.0000	0	0	0	0	0	0.3334	0	0	0	0	0	0	0	0	0	0	0
TR	0	0.0000	0.0000	0.4285	0	0.1090	0	0	0	0	0.3077	0.0981	0	0	0	0	0	0	0	0	0
VC	0	0.0000	0.0000	0.0715	0	0	0	0	0	0	0.0385	0.1961	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0.0585	0.0310	0.0740	0.0005	0.0555	0.0870	0.0155	0.0130	1	0	0	0	0	0	0	0	0
II	0	0	0	0	0.0590	0.0370	0.0705	0.0160	0.0555	0.0785	0.0250	0.0205	0	1	0	0	0	0	0	0	0
III	0	0	0	0	0.0590	0.0430	0.0665	0.0305	0.0555	0.0725	0.0350	0.0295	0	0	1	0	0	0	0	0	0
IV	0	0	0	0	0.0580	0.0480	0.0595	0.0440	0.0555	0.0640	0.0440	0.0480	0	0	0	1	0	0	0	0	0
V	0	0	0	0	0.0570	0.0540	0.0545	0.0570	0.0555	0.0550	0.0540	0.0595	0	0	0	0	1	0	0	0	0
VI	0	0	0	0	0.0565	0.0615	0.0515	0.0700	0.0555	0.0465	0.0655	0.0640	0	0	0	0	0	1	0	0	0
VII	0	0	0	0	0.0555	0.0680	0.0460	0.0825	0.0555	0.0465	0.0755	0.0780	0	0	0	0	0	0	1	0	0
VIII	0	0	0	0	0.0545	0.0740	0.0400	0.0950	0.0555	0.0290	0.0865	0.0930	0	0	0	0	0	0	0	1	0
IX	0	0	0	0	0.0415	0.0835	0.0380	0.1040	0.0555	0.0205	0.0995	0.0945	0	0	0	0	0	0	0	0	1

Table 16
The limit supermatrix for Case I, $\mathbf{M}_{\mathbf{I}}^{33}$

	Goal	Product	Equipment	Finance	WP	TP	TL	CT	BU	CU	TR	VC	I	II	III	IV	V	VI	VII	VIII	IX
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Product	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Equipment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Finance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I	0.0629	0.0899	0.1015	0.0454	0.0925	0.0592	0.1258	0.0163	0.0988	0.1552	0.0391	0.0514	1	0	0	0	0	0	0	0	0
II	0.0745	0.0963	0.1043	0.0605	0.099	0.0723	0.1246	0.0421	0.1021	0.144	0.0557	0.0635	0	1	0	0	0	0	0	0	0
III	0.0869	0.1024	0.1072	0.0769	0.1055	0.0856	0.1219	0.0679	0.1054	0.1358	0.0738	0.0767	0	0	1	0	0	0	0	0	0
IV	0.0984	0.1058	0.1089	0.0934	0.1095	0.0968	0.1142	0.0902	0.1082	0.123	0.0906	0.0998	0	0	0	1	0	0	0	0	0
V	0.1106	0.1108	0.1112	0.1102	0.1137	0.1095	0.1099	0.1129	0.1114	0.1103	0.1088	0.1162	0	0	0	0	1	0	0	0	0
VI	0.1246	0.1183	0.1147	0.1285	0.1196	0.1254	0.1093	0.1363	0.1153	0.0993	0.1301	0.124	0	0	0	0	0	1	0	0	0
VII	0.1371	0.123	0.118	0.1456	0.1238	0.1381	0.1035	0.159	0.1185	0.1001	0.1484	0.1427	0	0	0	0	0	0	1	0	0
VIII	0.1502	0.1273	0.119	0.1641	0.1276	0.1508	0.0977	0.1802	0.1217	0.074	0.1682	0.1628	0	0	0	0	0	0	0	1	0
IX	0.1639	0.133	0.1221	0.1828	0.1124	0.1664	0.0986	0.1976	0.1256	0.0629	0.1907	0.1674	0	0	0	0	0	0	0	0	1

Table 17
Overall priorities for the alternatives under different cases

Product mix (L:M)	Case I	Case II	Case III	Case IV
I: Mix (1:9)	0.0629	0.1175	0.1006	0.0562
II: Mix (2:8)	0.0745	0.1173	0.1049	0.072
III: Mix (3:7)	0.0869	0.1171	0.1084	0.0869
IV: Mix (4:6)	0.0984	0.1127	0.1081	0.0925
V: Mix (5:5)	0.1106	0.1115	0.1103	0.1065
VI: Mix (6:4)	0.1246	0.1112	0.1158	0.1271
VII: Mix (7:3)	0.1371	0.1094	0.1176	0.1397
VIII: Mix (8:2)	0.1502	0.1057	0.1182	0.151
IX: Mix (9:1)	0.1639	0.1059	0.1226	0.1764

Table 18
Ranking of the alternatives by *total revenue* and by ANP for Case III

Product mix (L:M)	Total revenue (US$)	Ranking by total revenue	Ranking by ANP
I: Mix (1:9)	18,630,000	2	9
II: Mix (2:8)	18,632,000	1	8
III: Mix (3:7)	18,626,000	3	7
IV: Mix (4:6)	18,546,000	5	6
V: Mix (5:5)	18,525,000	7	5
VI: Mix (6:4)	18,560,000	4	4
VII: Mix (7:3)	18,522,000	8	3
VIII: Mix (8:2)	18,476,000	9	2
IX: Mix (9:1)	18,544,000	6	1

manufactured in order to satisfy customer demand. Multiple priority orders, such as hot lots, rush lots and normal lots, are often encountered in fabs. As a result, the manufacturing environment can be even more complex.

Green production is especially important for semiconductor manufacturing and will determine the sustainability of a company in the long term. Semiconductor fabs use a lot of hazardous chemicals in their manufacturing process. Different product mixes require different chemicals and gases in the process, and the residual process gases and reactive by-products generally contain toxic and corrosive gases that may be harmful to the environment. As a result, the determination of a good product mix may not only include product, equipment efficiency and finance factors, environmental issues may also need to be taken into consideration. This can also be our future focus of research.

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Appendix A. Review of the ANP

The analytic hierarchy process (AHP) was developed by Saaty in 1971, and its purpose was to structure a decision process in a scenario influenced by multiple independent factors (Saaty, 1980). A complex problem can be decomposed into several sub-problems in terms of hierarchical levels, where each level represents a set of criteria or attributes relative to each sub-problem. The top level of the hierarchy is the goal of the problem, and the intermediate levels represent the factors of respective upper level. The last level contains the alternatives or actions to be considered in the achievement of the goal. AHP allows the factors to be compared with the importance of each factor relative to its impact on the solution of the problem. Since its introduction, AHP has been widely used in decision-making, and numerous applications have been published in literature (Shim, 1989).

The ANP, also introduced by Saaty, is a generalization of the AHP (Saaty, 1996). Whereas AHP represents a framework with a uni-directional hierarchical relationship, ANP allows for more complex interrelationships among decision levels and attributes. The ANP feedback approach replaces hierarchies with networks, in which the relationships between levels are not easily represented as higher or lower, dominated or being dominated, directly or indirectly (Meade and Sarkis, 1999). For instance, not only does the importance of the criteria determine the importance of the alternatives as in a hierarchy, but also the importance of the alternatives may have impact on the importance of the criteria (Saaty, 1996). Therefore, a hierarchical structure with a linear top-to-bottom form is not applicable for a complex system.

A system with feedback can be represented by a network where nodes correspond to the levels or components (Saaty, 1980). The structural difference between a hierarchy and a network is depicted in Fig. 8. The elements in a node (or level) may influence some or all the elements of any other node. In a network, there can be source nodes, intermediate nodes and sink nodes. Relationships in a network are represented by arcs, and the directions of arcs signify dependence (Saaty, 1996). Interdependency between two nodes, termed outer dependence, is represented by a two-way arrow, and inner dependencies among elements in a node are represented by a looped arc (Sarkis, 2002).

The process of ANP comprises four major steps (Meade and Sarkis, 1999; Saaty, 1996).

Step 1: *Model construction and problem structuring*: The problem should be stated clearly and decomposed into a rational system like a network. The structure can be obtained by the opinion of decision makers through brainstorming or other appropriate methods. An example of the format of a network is as shown in Fig. 8(b).

Step 2: *Pairwise comparisons matrices and priority vectors*: In ANP, like AHP, decision elements at each component are compared pairwise with respect to their importance towards their control criterion, and the components themselves are also compared pairwise with respect to their contribution to the goal. Decision makers are asked to respond to a series of pairwise comparisons where two elements or two components at a time will be compared in terms of how they contribute to their particular upper level criterion (Meade and Sarkis, 1999). In addition, if there are interdependencies among elements of a component, pairwise comparisons also need to be created, and an eigenvector can be obtained for each element to show the influence of other elements on it. The relative importance values are determined with a scale of 1 to 9, where a score of 1 represents equal importance between the two elements and a score of 9 indicates the extreme importance of one element (row component in the matrix) compared to the other one (column component in the matrix) (Meade and Sarkis, 1999). A reciprocal value is assigned to the inverse comparison; that is, $a_{ij} = 1/a_{ji}$, where $a_{ij}(a_{ji})$ denotes the importance of the ith (jth) element compared to the jth (ith) element. Like AHP, pairwise comparison in ANP is made in the framework of a matrix, and a local priority vector can be derived as an estimate of relative importance associated with the elements (or components) being compared by solving the following equation:

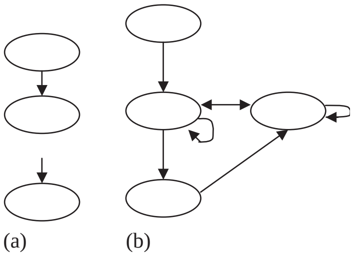

Fig. 8. Structural difference between a hierarchy and a network: (a) a hierarchy; (b) a network.

$$\mathbf{A} \cdot w = \lambda_{\max} \cdot w, \tag{A.1}$$

where **A** is the matrix of pairwise comparison, w is the eigenvector, and $\lambda_{\max}$ is the largest eigenvalue of **A**. Saaty (1980) proposes several algorithms for approximating w. In this paper, the following three-step procedure is used to synthesize priorities (Anderson et al., 1997; Meade and Presley, 2002; Saaty, 1980).

1. Sum the values in each column of the pairwise comparison matrix.
2. Divide each element in a column by the sum of its respective column. The resultant matrix is referred to as the normalized pairwise comparison matrix.
3. Sum the elements in each row of the normalized pairwise comparison matrix, and divide the sum by the n elements in the row. These final numbers provide an estimate of the relative priorities for the elements being compared with respect to its upper level criterion.

Priority vectors must be derived for all comparison matrices.

Step 3: *Supermatrix formation*: The supermatrix concept is similar to the Markov chain process (Saaty, 1996). To obtain global priorities in a system with interdependent influences, the local priority vectors are entered in the appropriate columns of a matrix, known as a supermatrix. As a result, a supermatrix is actually a partitioned matrix, where each matrix segment represents a relationship between two nodes (components or clusters) in a system (Meade and Sarkis, 1999). Let the components of a decision system be C_k, $k = 1, \ldots, n$, and each component k has m_k elements, denoted by $e_{k1}, e_{k2}, \ldots, e_{km_k}$. The local priority vectors obtained in Step 2 are grouped and located in appropriate positions in a supermatrix based on the flow of influence from a component to another component, or from a component to itself as in the loop. A standard form of a supermatrix is as in (A.2) (Saaty, 1996).

$$\mathbf{W} = \begin{array}{cc|ccccc} & & C_1 & \cdots & C_k & \cdots & C_n \\ & & e_{11}\ e_{12}\ \cdots\ e_{1m_1} & \cdots & e_{k1}\ e_{k2}\ \cdots\ e_{km_k} & \cdots & e_{n1}\ e_{n2}\ \cdots\ e_{nm_n} \\ \hline C_1 & \begin{matrix} e_{11} \\ e_{12} \\ \vdots \\ e_{1m_1} \end{matrix} & \mathbf{W}_{11} & \cdots & \mathbf{W}_{1k} & \cdots & \mathbf{W}_{1n} \\ \vdots & \vdots & \vdots & & \vdots & & \vdots \\ C_k & \begin{matrix} e_{k1} \\ e_{k2} \\ \vdots \\ e_{km_k} \end{matrix} & \mathbf{W}_{k1} & \cdots & \mathbf{W}_{kk} & \cdots & \mathbf{W}_{kn} \\ \vdots & \vdots & \vdots & & \vdots & & \vdots \\ C_n & \begin{matrix} e_{n1} \\ e_{n2} \\ \vdots \\ e_{nm_n} \end{matrix} & \mathbf{W}_{n1} & \cdots & \mathbf{W}_{nk} & \cdots & \mathbf{W}_{nn} \end{array} \qquad \text{(A.2)}$$

As an example, the supermatrix representation of a hierarchy with three levels as shown in Fig. 9(a), is as follows (Saaty, 1996):

$$\mathbf{W}_h = \begin{bmatrix} 0 & 0 & 0 \\ w_{21} & 0 & 0 \\ 0 & \mathbf{W}_{32} & \mathbf{I} \end{bmatrix}, \qquad \text{(A.3)}$$

where w_{21} is a vector that represents the impact of the goal on the criteria, $\mathbf{W}_{32}$ is a matrix that represents the impact of criteria on each of the alternatives, $\mathbf{I}$ is the identity matrix, and entries of zeros corresponding to those elements that have no influence.

For the above example, if the criteria are interrelated among themselves, the hierarchy is replaced by a network as shown in Fig. 9(b). The (2, 2) entry of $\mathbf{W}_n$ given by $\mathbf{W}_{22}$ would indicate the interdependency, and the supermatrix would be (Saaty, 1996)

$$\mathbf{W}_n = \begin{bmatrix} 0 & 0 & 0 \\ w_{21} & \mathbf{W}_{22} & 0 \\ 0 & \mathbf{W}_{32} & \mathbf{I} \end{bmatrix}. \qquad \text{(A.4)}$$

Note that any zero in the supermatrix can be replaced by a matrix if there is an interrelationship

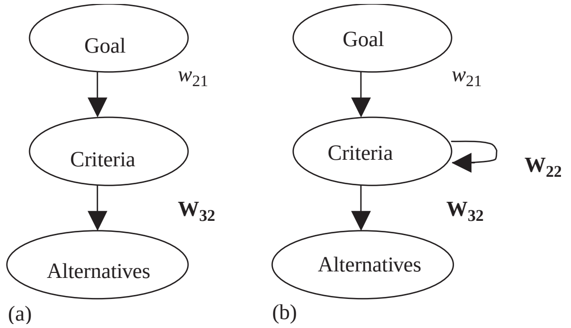

Fig. 9. Hierarchy and Network (Momoh and Zhu, 1998): (a) a hierarchy; (b) a network.

of the elements in a component or between two components. Since there usually is interdependence among clusters in a network, the columns of a supermatrix usually sum to more than one. The supermatrix must be transformed first to make it stochastic, that is, each column of the matrix sums to unity. A recommended approach by Saaty (1996) is to determine the relative importance of the clusters in the supermatrix with the column cluster (block) as the controlling component (Meade and Sarkis, 1999). That is, the row components with nonzero entries for their blocks in that column block are compared according to their impact on the component of that column block (Saaty, 1996). With pairwise comparison matrix of the row components with respect to the column component, an eigenvector can be obtained. This process gives rise to an eigenvector for each column block. For each column block, the first entry of the respective eigenvector is multiplied by all the elements in the first block of that column, the second by all the elements in the second block of that column and so on. In this way, the blocks in each column of the supermatrix is weighted, and the result is known as the weighted supermatrix, which is stochastic.

Raising a matrix to powers gives the long-term relative influences of the elements on each other. To achieve a convergence on the importance weights, the weighted supermatrix is raised to the power of $2k+1$, where k is an arbitrarily large number, and this new matrix is called the limit supermatrix (Saaty, 1996). The limit supermatrix has the same form as the weighted supermatrix, but all the columns of the limit supermatrix are the same. By normalizing each block of this supermatrix, the final priorities of all the elements in the matrix can be obtained.

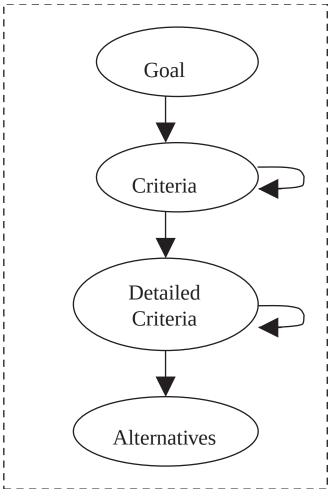

Fig. 10. Network form for this paper.

Step 4: *Selection of best alternatives*: If the supermatrix formed in Step 3 covers the whole network, the priority weights of alternatives can be found in the column of alternatives in the normalized supermatrix. On the other hand, if a supermatrix only comprises of components that are interrelated, additional calculation must be made to obtain the overall priorities of the alternatives. The alternative with the largest overall priority should be the one selected. In this paper, the first method is applied, and a supermatrix that covers the whole network as shown by the bracket in Fig. 10, is formed.

Appendix B. Pairwise comparisons

In this paper, a total of 15 pairwise comparisons are involved. The goal and criteria for each pairwise comparison are listed as in Table 19.

Table 19
Pairwise comparisons considered

	Goal	Criteria
1	To achieve the most efficient manufacturing performance	Product, equipment efficiency and finance
2	To achieve the best performance in *product* (assuming no interdependence among factors)	WIP (WP), throughput (TP), total layers (TL) and total cycle time (CT)
3	To achieve the best *equipment utilization* (assuming no interdependence among factors)	Bottleneck utilization (BU) and CCR utilization (CU)
4	To achieve the best performance in *finance* (assuming no interdependence among factors)	Total revenue (TR) and total variable costs (VC)
5	Inner dependence of criteria with respect to *product*	Product, equipment efficiency and finance
6	Inner dependence of criteria with respect to *equipment efficiency*	Product, equipment efficiency and finance
7	Inner dependence of criteria with respect to *finance*	Product, equipment efficiency and finance
8	Inner dependence of detailed criteria with respect to WP	WP, TP, TL, CT, BU, CU, TR, VC
9	Inner dependence of detailed criteria with respect to TP	WP, TP, TL, CT, BU, CU, TR, VC
10	Inner dependence of detailed criteria with respect to TL	WP, TP, TL, CT, BU, CU, TR, VC
11	Inner dependence of detailed criteria with respect to CT	WP, TP, TL, CT, BU, CU, TR, VC
12	Inner dependence of detailed criteria with respect to BU	WP, TP, TL, CT, BU, CU, TR, VC
13	Inner dependence of detailed criteria with respect to CU	WP, TP, TL, CT, BU, CU, TR, VC
14	Inner dependence of detailed criteria with respect to TR	WP, TP, TL, CT, BU, CU, TR, VC
15	Inner dependence of detailed criteria with respect to VC	WP, TP, TL, CT, BU, CU, TR, VC

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