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ORIGINAL ARTICLE

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Product Mix Optimization for Semiconductor Manufacturing Based on AHP and ANP Analysis

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Abstract In a competitive market, a company needs to utilize its available capacity efficiently in order to acquire high profit. The purpose of this paper is to present effective approaches to find a set of product mix optimal for the company to achieve the optimal manufacturing. Analytic hierarchy process (AHP) and analytic network process (ANP) approaches are taken to analyse multiple process inputs and outputs, incorporating experts' opinion on their priority of importance, to obtain optimal product mixes for semiconductor production. The results provide guidance to the fabricator regarding strategies for accepting orders to maximize the manufacturing efficiency and the profit, while simultaneously considering other important input and output factors for maintaining manufacturing smoothness.

Keywords Analytic hierarchy process · Analytic network process · Efficiency · Product mix · Semiconductor fabricator

1 Introduction

In order to survive in the competitive market, semiconductor manufacturing companies must increase or at least maintain their overall profit and return on investment. One basic task is to utilize existing capacity efficiently and effectively. The purpose of this paper is to present an effective approach to find a set of optimal product mix that is feasible for production, which can be accepted by the semiconductor fabricator. The analysis is aimed at the strategic planning level and attempts to assess manufacturing performance under various product mixes. A simulation model is first developed to collect the relevant performance outcomes under different product mixes. The AHP approach is first performed to evaluate various factors for different product mixes, to provide relative significance measures for each product mix. Then, the ANP, a general approach of AHP, is applied to analyse more complex interrelationships among the decision levels and attributes, and is also applied in our case study.

The rest of this paper is organized as follows. Section 2 gives an overall review of the manufacturing environment and description of the product mix problem in semiconductor industry. Section 3 briefly reviews the decision-making tool AHP. Section 4 describes the basics of ANP and presents a simplified version of the ANP approach. Section 5 discusses the process parameters selected for evaluation. Section 6 presents the system environment for simulation. Sections 7 and 8 apply AHP and ANP to evaluate the data obtained from simulation. In Sect. 9, some conclusion remarks are made.

2 Manufacturing environment and product mix problem

Semiconductor industry today faces a very dynamic environment. Product demand changes rapidly, while product life cycles are shortened. New process and machine technologies are developed rapidly, and building new fabs and expanding fab capacity enter the already competitive market continuously. Like firms in other industries, semiconductor companies must meet customers' ever-rising demands in order to survive. Failure to deliver product on time, with the right quality and quantity, can result in profit penalties or even losing customers. The length and variability of cycle times are important factors in the measurement of customer service. Semiconductor companies can be successful if they only focus on either of the two types: mass manufacturing with high volume and low cost, or a high level of product mix that is flexible [25]. In today's semiconductor fabs, a wide range of logic and memory products are manufactured, and up to several dozen different product types with more than hundreds of derivatives can be processed simultaneously. High-volume, low-cost fabs produce only a few kinds of products, such as DRAM, in large quantity in order to have economies of scale; while high-mix, flexible fabs mainly produce customer specific chips ("make-to-order") and aim to leverage economies of scope.

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Modern fabs require a very high capital investment in plant and equipment, some 500 million US $ to 1 billion US $ each [13]. The tremendous amount of investment makes the manufacturers try every possibility for fully utilizing the facility. In the time of suppliers' market, a small increase in production capacity often means large additional profits and higher market share. Efficient wafer fabrication often requires continuing phases of expansion, new knowledge and skill adoption and process improvement. Wafer manufacturing process is highly complex, with several hundred processing steps on a single wafer and a flow time of usually more than one month. Some machine groups may be used for the same operation more than once as successive circuit layers are added. Such operations of multiple visits to the same machine group is termed the re-entry property of the manufacturing flow [3]. The manufacturing flow of different products may differ significantly, and the processing time required of the machines for one type of product may be twice as much as that required for the other type of product [6]. Wafer fabs involve the most complex manufacturing system in the manufacturing world. The dynamics, varieties in processes, machines, and product demands often cause manufacturing bottlenecks to shift from one resource to another. All the factors discussed above are interrelated resulting in a complicated production planning problem for the semiconductor fabs.

Manufacturing planning involving product mix is a common problem often encountered in manufacturing which used to be formulated classically, as a linear programming problem. The objective of such a problem is to maximize the profit from various product mix combinations, subject to constraints on different resources [17]. Manufacturing a product requires a certain amount of resource of each type that is limited. The availability of each resource, therefore, is a constraint. In the past decade, the theory of constraints (TOC) has also been a popular approach for dealing with the product mix planning problem [9]. Based on the TOC, there exists at least one bottleneck resource in the system that critically impacts the system performance [11]. Due to the mutually dependent characteristics of various manufacturing events, the output of the system is constrained by the bottleneck resource. In order to acquire the highest profit attainable, the bottleneck resource must be fully utilized. It is known that the linear programming and TOC approaches are different in their implementation procedures but both methods are conceptually equivalent and lead to the same solutions [15]. Two aspects most researchers have focussed on in finding the optimal product mix are cost accounting and manufacturing planning. Cost accounting involves estimating the manufacturing cost of each product type appropriately to find a product mix that maximizes the company's profit. Malik [17] developed a mixed-integer programming model utilizing activity-based cost information to determine optimal product mix and product cost in a multi-product manufacturing environment. The second aspect, manufacturing planning, involves maximizing the efficiency of capacity allocation across products. Chou et al. [6] formulated a mixed-integer linear programming to optimize the product mix, taking into consideration the requirement of manufacturing smoothing and machine backup.

Manufacturing planning involving product mix in semiconductor industry is a complicated problem. In a semiconductor fab, machines are shared by a huge number of different products, resulting in a heavy load sharing the precious resource and consequently complex queuing may be present. Product mix level has considerable impact on production throughput, cycle time and the capability of meeting due dates, which are the most important metrics for measuring manufacturing performance [8]. Production throughput, cycle time, machine utilization and work in process (WIP) inventory are highly interrelated. Some measurement criteria are positively dependent, and others may be (negatively dependent) trade-offs. For example, it is desirable to have both high throughput and low cycle time. But those two measures tend to conflict with each other. If we emphasize the increase of system throughput, the WIP level must be increased. Even though machines can be utilized more and high equipment utilization indicates high return from investment, which is favourable, the bottleneck machine may not have enough capacity to handle such demand, and so the WIP at the bottleneck must be at an excessive level. As a result, cycle time of products will be significant, on-time deliveries will be decreased, and market responsiveness is diminished. Production throughput, the index we stress primarily, may even decrease ultimately. Under different product mixes, the manufacturing performance of the system will be different, and AHP/ANP will be used to evaluate which product mix would result in a more competitive manufacturing performance and a better overall outcome for the wafer fab.

3 Review of the AHP

AHP, a mathematically based multi-criteria decision-making tool, is becoming popular with academic researchers for data analysis, model verifications to provide critical information for managers to make business decisions. AHP was originally introduced by Saaty [21–23] back in the early 1970s in response to the scarce resources allocation and planning needs for the military [21]. The AHP comprises six major steps [5, 21, 22]:

1. Define the unstructured problem. The problem should be stated clearly and be put in broad context including the objectives and the outcomes.
2. Decompose the problem into a hierarchical structure. AHP decomposes a complex problem into a decision hierarchy much like a decision tree. The overall objective of the problem, the top level of the hierarchy, can be decomposed into several criteria or attributes, a lower level of the hierarchy. Each next lower level represents the increased detail of these criteria or attributes and there can be several intermediate levels as required until no further decomposition is required. The bottom of the hierarchy usually represents alternatives or actions to be considered to solve the problem. A standard format for AHP decision model is illustrated in Fig. 1. The structure of the hierarchy can be obtained by the opinion of experts or decision makers with a method such as brainstorming.

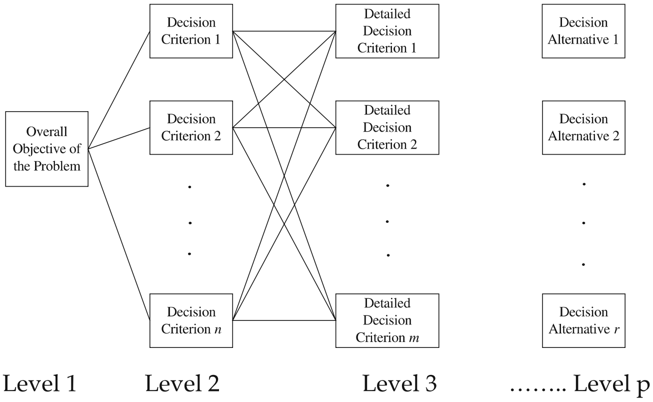


Fig. 1. A standard hierarchy for AHP

3. Employ pairwise comparisons. Decision elements at each hierarchy level are compared pairwise and assigned relative scales. Decision makers will be asked to compare each of the paired elements in the matrices through questionnaires. At the first level, they need to specify judgments about the relative importance of each criterion in terms of its contribution to achieving the overall objective. At the each next level, they need to indicate a priority for each detailed decision criterion in terms of how it contributes to each criterion. At the last level, a preference for each decision alternative in terms of how it contributes to each subcriterion must be made. Saaty [21] recommended the use of a nine-point scale to express preferences between options as equally, moderately, strongly, very strongly, or extremely preferred (with pairwise weights of 1, 3, 5, 7 and 9 respectively). Values of 2, 4, 6 and 8 are the intermediate values for the preference scale. Reciprocals are used for the inverse comparisons. After each element has been compared, a paired comparison matrix is formed. If n objects, denoted by $X_1, X_2, X_3, \dots, X_n$, are compared in pairs according to their relative weights, denoted by $w_1, w_2, w_3, \dots, w_n$, respectively, the pairwise comparisons can be represented in the form of a matrix [1, 21].
   $X_1, X_2, X_3, \dots, X_n$, are compared in pairs according to their relative weights, denoted by $w_1, w_2, w_3, \dots, w_n$, respectively, the pairwise comparisons can be represented in the form of a matrix [1, 21] .

$$\boldsymbol{A} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

4. Find the maximum eigenvalues and eigenvectors in order to estimate the relative weights of the decision elements. After a comparison matrix has been formed, the priority of the element can be compared by the computation of eigenvalues and eigenvectors with the following formula, where w is the eigenvector, the weight vector, of $\boldsymbol{A}$, and $\lambda_{\max}$ is the largest eigenvalue of $\boldsymbol{A}$:

$$\boldsymbol{A} \cdot w = \lambda_{\max} \cdot w \tag{2}$$

5. Check the consistency property of the matrix. The quality of ultimate decision of AHP process is strongly related to the consistency of judgments that decision makers demonstrated during the series of pairwise comparisons [2]. Transitivity of preference implies that if A is preferred to B, and B is preferred to C, then A is preferred to C. This consistency property in the pairwise comparison is examined by the consistency ratio. The consistency index (CI) and consistency ratio (CR) are defined as [21]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

$$CR = \frac{CI}{\mathrm{RI}}\,, \tag{4}$$

   where n is the number of items being compared in the matrix, and RI is a random index, the average consistency index of randomly generated pairwise comparison matrices of similar size, as shown in Table 1. Satty [22] has set the acceptable CR values for different matrix sizes. The threshold CR values are 0.05 for a 3×3 matrix, 0.08 for a 4×4 matrix, and 0.10 for larger matrices. When the calculated CR values exceed the threshold, it is an indication of inconsistent judgment. In such cases, the decision makers would need to revise the original values in the pairwise comparison matrix.
6. Aggregate the relative priorities of the decision elements to obtain an overall rating for decision alternatives. If there is only one decision maker, an overall priority ranking of the decision alternatives can be obtained by combining the criterion priorities and priorities of each decision alternative relative to each criterion. The results are normalized and summed to 1. The alternative with a higher rating is considered to be preferable. In the case of a group with more than one decision maker, an overall priority ranking will be generated for each person first, and a weighted average method will be applied to summarize individual rankings to determine the finalized preferential ranking of alternatives.

AHP has been widely employed in decision-making analysis in various fields such as political, social, economic and management sciences. In the field of manufacturing, AHP has been used in technology selection [20], the semiconductor facility layout design process [19, 27], plant location selection [28] and justification of flexible manufacturing systems [4], just to name a few. AHP combines both qualitative and quantitative approaches [5]. In the qualitative sense, it decomposes an unstructured problem

Table 1. Random index (RI) [22]

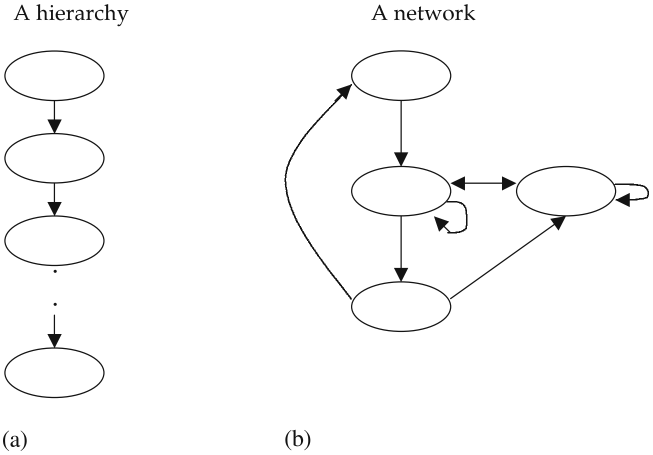
Order of matrix (n)	2	3	4	5	6	7	8
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41

into a systematic decision hierarchy. It then uses a quantitative way to employ pairwise comparison to determine the local and global priority weights and the overall ranking of the alternatives. We will use AHP as our tool to measure the manufacturing performance of the system under different product mixes.

4 Review of the ANP

The analytic network process (ANP) generalizes AHP by replacing hierarchies with networks [12]. It is the extension of AHP and is a more general form of AHP. ANP still involves the representation of relationships hierarchically, but it does not require as strict a hierarchical structure as AHP [18]. A major assumption of AHP is that each element in the hierarchy is supposed to be independent; however, in many cases, there is interdependence among criteria and alternatives [23]. Many researchers simply disregard this assumption of independence and still adopt AHP for their analysis. The use of AHP in this way means that the models lack the consideration of important interactions among and between decision-making levels [18]. Nonetheless, we cannot tell how good our results are unless we avoid oversimplifying and deal with the issue of dependence properly [24]. Figure 2 depicts the structural difference between a hierarchy and a network. A node represents a component (or cluster) with elements inside it, and an arc denotes the interaction between two components [12] . The direction of an arc represents dependence; a two-way arrow indicates interdependency between two components; and a loop shows the inner dependence of elements within a component. Figure 2a is the same hierarchy as shown in Fig. 1 and is a simple case of a network.

Saaty [21, 23] introduces the "supermatrix", similar to Markov chains, to handle the interdependence characteristics among elements and components. Let the components (clusters) of a decision system be $C_h,\ h = 1, \ldots, n$, and let each component h have m_h elements, denoted by $e_{h1}, e_{h2}, \ldots, e_{hm_n}$. The influence of a set of elements belonging to a component, on any element from another component, can be represented as a priority vector by applying pairwise comparisons in the same way as the AHP. These priority vectors 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 follows [23].



(a) (b)

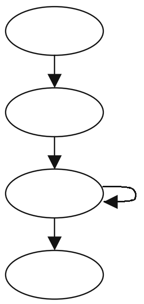
Fig. 2. Structural difference between a hierarchy and a network

$$
\begin{array}{cc}
 & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \\ e_{11}\,e_{12}\cdots e_{1m_1} & e_{21}\,e_{22}\cdots e_{2m_1} & \cdots & e_{31}\,e_{32}\cdots e_{3m_1} \end{array} \\
W = \begin{array}{cc} & e_{11} \\ C_1 & e_{12} \\ & \vdots \\ & e_{1m_1} \\ & e_{21} \\ & e_{22} \\ C_2 & \vdots \\ & e_{2m_2} \\ \vdots & \vdots \\ & e_{n1} \\ C_n & e_{n2} \\ & \vdots \\ & e_{nm_n} \end{array} & \left[\begin{array}{cccc} \boldsymbol{W}_{11} & \boldsymbol{W}_{12} & \cdots & \boldsymbol{W}_{1n} \\ \boldsymbol{W}_{21} & \boldsymbol{W}_{22} & \cdots & \boldsymbol{W}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{W}_{n1} & \boldsymbol{W}_{n2} & \cdots & \boldsymbol{W}_{nn} \end{array}\right]
\end{array}
$$

If the supermatrix is column stochastic, that is, if we can assume that its components have been weighted according to their contribution to the system, we can simply raise the supermatrix to powers to obtain the answer [23]. Otherwise, we need to generate a weighted supermatrix first, and then raise it to powers. When a network is not too complicated, a simplified method may be employed. Saaty et al. [24] devised a matrix manipulation approach to solve a network which is very similar to a hierarchy, with the only difference of dependence among criteria and dependence among alternatives with respect to each criterion. Lee et al. [14] suggested an information system project selection methodology, which reflects interdependencies among evaluation criteria and candidate projects using the above cited ANP approach within a zero-one goal-programming (ZOGP) model. Karsak et al. [12] also used a combined ANP and goal-programming approach for product planning in quality function deployment. In this paper, we adopt Saaty's [24] matrix manipulation concept and suggest an approach that is suitable for our problem with a network as shown in Fig. 3. The procedures are as follows:

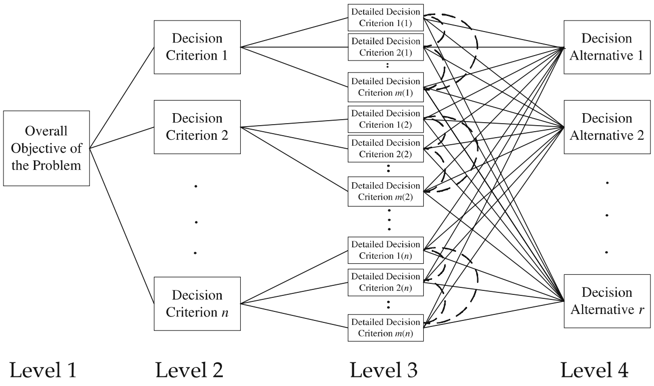
1. Determine the importance of each decision criteria with respect to attaining the overall objective. To compare the decision criteria, experts need to answer the question: "which decision criteria should be emphasized more in attaining the overall objective, and how much more?". By pairwise comparison of criteria with respect to the overall objective, we can obtain a matrix $(\boldsymbol{W}_1)$ and an eigenvector (w_1) of the ma-

A simplified network



(a)

A standard network for (a)



(b)

Fig. 3. A standard network for this paper

trix for the criteria:

$$
\boldsymbol{W}_1 = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array}
\begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \left[\begin{array}{cccc} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{array}\right] \end{array}
\quad \text{and} \quad
w_1 = \begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_n \end{array} \left[\begin{array}{c} c_1 \\ c_2 \\ \vdots \\ c_n \end{array}\right],
$$

where n is the number of criteria.

2. Determine the importance of each detailed criteria with respect to its upper level criteria by assuming that there is no dependence among detailed criteria. To compare the detailed decision criteria, we need to know which detailed criteria should be emphasized more in determining their respective upper level criterion. The matrix and the eigenvector with respect to an upper level criterion (n) are as follows:

$$
\boldsymbol{W}_{2n} = \begin{array}{c} \\ D_{1(n)} \\ D_{2(n)} \\ \vdots \\ D_{m(n)} \end{array}
\begin{array}{c} \begin{array}{cccc} D_{1(n)} & D_{2(n)} & \cdots & D_{m(n)} \end{array} \\ \left[\begin{array}{cccc} d_{11(n)} & d_{12(n)} & \cdots & d_{1m(n)} \\ d_{21(n)} & d_{22(n)} & \cdots & d_{2m(n)} \\ \vdots & \vdots & \vdots & \vdots \\ d_{m1(n)} & d_{m2(n)} & \cdots & d_{mm(n)} \end{array}\right] \end{array}
$$

$$
\text{and} \quad w_{2n} = \begin{array}{c} D_{1(n)} \\ D_{2(n)} \\ \vdots \\ C_{m(n)} \end{array} \left[\begin{array}{c} d_{1(n)} \\ d_{2(n)} \\ \vdots \\ d_{m(n)} \end{array}\right], \text{ for each } n
$$

where $m(n)$ is the number of detailed criteria with respect to an upper level n, and the total number of detailed criteria m is equal to the sum of all $m(n)$, that is, $m = m(1) + m(2) + \ldots m(n)$.

3. The priorities of alternatives with respect to each of the detailed criterion are obtained and the general form of matrix and eigenvector are as follows:

$$
\boldsymbol{W}_{bm} = \begin{array}{c} \\ B_{1(m)} \\ B_{2(m)} \\ \vdots \\ B_{r(m)} \end{array}
\begin{array}{c} \begin{array}{cccc} B_{1(m)} & B_{2(m)} & \cdots & B_{r(m)} \end{array} \\ \left[\begin{array}{cccc} b_{11(m)} & b_{12(m)} & \cdots & b_{1r(m)} \\ b_{21(m)} & b_{22(m)} & \cdots & b_{2r(m)} \\ \vdots & \vdots & \vdots & \vdots \\ b_{r1(m)} & b_{r2(m)} & \cdots & b_{rr(m)} \end{array}\right] \end{array}
$$

$$
\text{and} \quad w_{bm} = \begin{array}{c} B_{1(m)} \\ B_{2(m)} \\ \vdots \\ B_{r(m)} \end{array} \left[\begin{array}{c} b_{1(m)} \\ b_{2(m)} \\ \vdots \\ b_{r(m)} \end{array}\right], \text{ for each } m \text{ },
$$

where r is the number of alternatives. We next combine the above eigenvectors with respect to the criterion n and obtain the following matrix:

$$
\boldsymbol{W}_{3n} = \begin{array}{c} \\ B_1 \\ B_2 \\ \vdots \\ B_r \end{array}
\begin{array}{c} \begin{array}{cccc} D_{1(n)} & D_{2(n)} & \cdots & D_{m(n)} \end{array} \\ \left[\begin{array}{cccc} b_{1(1)} & b_{1(2)} & \cdots & b_{1(m)} \\ b_{2(1)} & b_{2(2)} & \cdots & b_{2(m)} \\ \vdots & \vdots & \vdots & \vdots \\ b_{r(1)} & b_{r(2)} & \cdots & b_{r(m)} \end{array}\right] \end{array}
\quad \text{for each } n \text{ }.
$$

4. Analyse the interdependence among the detailed criteria. The inner dependence among detailed criteria under the same criterion are determined through analysing the impact of each detailed criterion on other detailed criteria with the same upper level criterion. Pairwise comparisons through experts' opinion are applied in the literature [12, 14, 24]. In this paper, however, a correlation analysis is performed instead. We define the interdependence weight matrix of detailed criteria with the same upper level criterion as:

$$
\boldsymbol{W}_{4n} = \begin{array}{c} \\ D_{1(n)} \\ D_{2(n)} \\ \vdots \\ D_{m(n)} \end{array}
\begin{array}{c} \begin{array}{cccc} D_{1(n)} & D_{2(n)} & \cdots & D_{m(n)} \end{array} \\ \left[\begin{array}{cccc} v_{11(n)} & v_{12(n)} & \cdots & v_{1m(n)} \\ v_{21(n)} & v_{22(n)} & \cdots & v_{2m(n)} \\ \vdots & \vdots & \vdots & \vdots \\ v_{m1(n)} & v_{m2(n)} & \cdots & v_{mm(n)} \end{array}\right] \end{array}
$$

for each n .

5. Obtain the interdependence priorities, $w_{DC(n)}$, of the detailed criteria by synthesizing the results from Step 2 and Step 4. $w_{DC(n)} = \boldsymbol{W}_{4n} \times w_{2n}$ for each n.
6. The priorities of alternatives, $w_{21(n)}$, with respect to each of the three criteria are given by synthesizing the results

from Step 3 and Step 5 as follows: $w_{21(n)} = \boldsymbol{W}_{3n} \times w_{DC(n)}$ for each n. We then define the matrix W_{21} by grouping together the above three columns of $w_{21(n)}$ for all ns: $\boldsymbol{W}_{21} = \left(w_{21(1)}, w_{21(2)}, \ldots, w_{21(n)}\right)$

7. The overall priorities for the alternatives are obtained by synthesizing the results from Step 1 and Step 6; that is, multiplying $\boldsymbol{W}_{21}$ by w_1. $w^{\mathrm{ANP}} = \boldsymbol{W}_{21} \times w_1$.

The ANP analysis results will be (alternative 1, alternative 2, . . . , alternative n). The above procedures are specifically designed to fit our problem and will be applied in the evaluation in Sect. 8.

5 Process parameters for evaluation

Depending on the comparison criterion used, some product mixes may perform better than the others. Without knowledge of the relative importance of these criteria, it is difficult to decide what product mix should be applied in a fab to achieve the optimal manufacturing results. Based on the AHP method, experts are interviewed first to decide the major criteria and the subsequent detailed criteria for evaluating performance under different product mixes for product A and B. A hierarchical structure, which consists of three major criteria and numerous detailed criteria, is established as shown in Fig. 2.

The three major criteria and the detailed criteria we used to measure manufacturing performance of a semiconductor fab are defined as follows:

1. *Product* How products are manufactured in a fab.
    - *WIP* The number of lots of manufacturing that have been released into the wafer fab but have not yet finished being processing through all of their manufacturing steps.
    - *Throughput* The number of lots of manufacturing that pass through the final operation step in a period.
    - *Total layers* The number of layers the bottleneck processed in a period of time.
    - *Total cycle time* The duration of time, expressed in hours, consumed by a unit of manufacturing 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.
2. *Equipment Efficiency* How effective the equipment is used in manufacturing, a measure of equipment performance.
    - *BN utilization* shows average utilization rate of the bottleneck in the system for a period of time. At the bottleneck workstation, equipment utilization should be as high as possible since it gates the throughput of the entire manufacturing system.
    - *CCR utilization* shows average utilization rate of the CCR in the system for a period of time. A CCR is a workstation which, although it is not a bottleneck, also has a substantially high utilization rate.
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. The price for a product is set by its product type and the number of layers that product goes through. Most manufacturing costs of a semiconductor fabricator are fixed; that is, no matter how many products are produced, the operating costs do not vary much.
    - *Total revenue* 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 by its throughput.
    - *Variable costs* 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 cost includes 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 semiconductor manufacturing companies located on the Science-Based Industrial Park in Taiwan and academic researches were involved in evaluating the criteria and sub-criteria and gave pairwise comparison values.

6 System input and simulation

To obtain a set of product mix that is optimal for factory manufacturing, actual data is collected from a wafer fabrication factory located on the Science-Based Industrial Park in Taiwan. Simulation results are used to estimate the manufacturing performance. To simplify the complexity of the environment for our analysis, this paper is based on the following assumptions. The fab produces two types of products, A and B. The process of each product type is different and unique. Both products are logic products. There is only one priority level of products; that is, all products are normal. Product A requires 305 operations and passes through the bottleneck 17 times. That is, 18 layers are processed. Product B requires 345 operations and passes through the bottleneck 19 times (20 layers processed). There are two types of machines: batch and serial. A total of 83 workstations (W1 to W83) are in the manufacturing environment. Preventive maintenance is considered in estimating usable manufacturing capacity. WS46, a stepper in the photolithography area, is the bottleneck.

The CCR is a machine with a high utilization rate that is close to that of the bottleneck. The strategy of manufacturing is to maximize the utilization of the bottleneck. The dispatching rule is first-in, first-out (FIFO). The releasing batch size for normal lots is six lots. Such a setting is 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. Product price is determined according to the number of layers the product processed

Wafer lots are released under CONWIP (CONstant WIP), a fixed work-in- process (WIP) policy. For production smoothing, that is, to minimize cycle time variation, constant WIP control is adopted for setting the suitable system WIP level of wafer lots, L [25]. Little's Law [15] in queuing theory, $L = \lambda \times W$, is applied, where λ is the releasing rate and W is the production cycle time. By adopting constant WIP control policy, wafer lot(s) can be released to shop floor only when the same quantity of wafers are finished and transferred out. That is, no new job is allowed to enter the system until a job leaves.

Because different products go through different processes, the charged price is set to be \$ 40 per pass through the bottleneck for product A, and \$ 42 for product B. 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 be \$ 7.5 per layer for product A, and \$ 8 per layer for product B. 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 data obtained from running simulations for each product mix (represented by I to IX) with manufacturing ratio of A to B is shown in Table 2. The data is to be used in AHP and ANP analysis in the next two sections.

7 AHP for product mix determination

Senior managers and experts contributed their professional experience to identify criteria and sub-criteria that influence the decision. The hierarchical form of determining the efficient manufacturing performance has already been shown in Fig. 4. Note that each element in the hierarchy is assumed to be independent. The next step is to construct the comparison matrices at each level of the hierarchy for pairwise comparison of the factors in that level. The Delphi method was performed to obtain a consensus among the people who were involved [9]. To arrive at a group position regarding an issue, the Delphi method consisted of a series of repeated interrogations through questionnaires of a group of experts and managers whose judgments were of interest. After the initial interrogation of each individual, each subsequent interrogation was accompanied by information regarding the preceding round of replies, and each individual was encouraged to reconsider and change his previous reply in light of the replies of other members of the group. The group position was finally determined after several rounds. 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. The pairwise comparison results are shown in Table 3, and the comparison matrix for comparing the criteria in level 2 in terms of their contribution to achieving the overall objective is shown in Table 4.

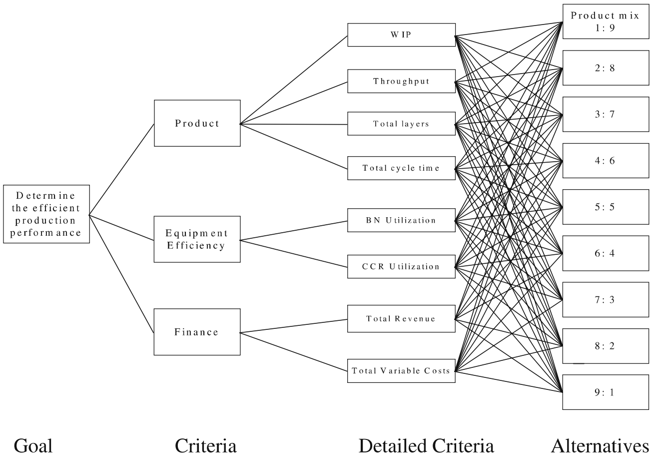


Fig. 4. The hierarchical framework of factors

An eigenvector and an eigenvalue are calculated using the eigenvalue method by Equation Eq. 1.

$$w_1 = \begin{array}{c} P \\ E \\ F \end{array} \begin{bmatrix} 0.258 \\ 0.105 \\ 0.637 \end{bmatrix} \quad \text{and} \quad \lambda_{\max} = 3.04\,.$$

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 third with weights of 0.258 and 0.105. To check the consistency of this combination of values in

Table 2. Simulation results

Product mix (A:B)	WIP (lots)	Throughput (TP) (lots)	Total layers (TL)	Total cycle time (CT) (hours)	BN utilization (BU) (%)	CCR utilization (CU) (%)	Total revenue (TR) (\$)	Variable costs (VC) (\$)
I: Mix (1:9)	274.89	600	11,880	307.9	0.99	0.86	12,420,000	3,883,068
II: Mix (2:8)	277.22	612	11,995	304.41	0.99	0.85	12,484,800	3,922,333
III: Mix (3:7)	276.32	620	12,028	299.49	0.99	0.84	12,462,000	3,934,707
IV: Mix (4:6)	272.73	624	11,981	293.69	0.99	0.83	12,355,200	3,920,942
V: Mix (5:5)	271.22	630	11,970	286.79	0.99	0.81	12,285,000	3,919,118
VI: Mix (6:4)	272.83	640	12,032	286.46	0.99	0.8	12,288,000	3,941,173
VII: Mix (7:3)	273.16	648	12,053	283.27	0.99	0.79	12,247,200	3,949,782
VIII: Mix (8:2)	276.38	660	12,144	281.34	0.99	0.78	12,276,000	3,981,518
IX: Mix (9:1)	276.97	668	12,158	278.63	0.99	0.76	12,224,400	3,987,868

Table 3. 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

In order to achieve the best manufacturing, which factor 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	
WIP											X							Throughput
WIP											X							Total layers
WIP								X										Total cycle time
Throughput											X							Total layers
Throughput						X												Total cycle time
Total layers						X												Total cycle time

In order to best utilize the equipment, which factor 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	
BN utilization	X																	CCR utilization

In order to achieve the best performance in finance, which factor 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	
Total revenue				X														Total variable costs

Table 4. 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

the matrix, $\lambda_{\max}$ is substituted into Eq. 3 to obtain CI, and CR is calculated by Eq. 4.

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{3.04-3}{3-1} = 0.02\,,$$

$$CR = \frac{CI}{\mathrm{RI}} = \frac{0.02}{0.58} = 0.03\,.$$

Since CR is less than 0.5, the threshold for a 3×3 matrix, the comparison matrix is consistent. The comparison matrices of detailed criteria in accordance to their respective upper level criteria (*product*, *equipment*, *finance*), their eigenvectors and consistent ratios are obtained and shown in Tables 5 to 7. For the criteria *product*, 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 simulation data from Table 2 are used to form the comparison matrices of alternatives (product mixes) with respect to each detailed criteria (*WIP*, *throughput*, etc.). Instead of asking senior managers and experts to identify the relative score of the alternatives with respect to each of the detailed criteria, simulation data, which indicate the manufacturing performance of a fab under different product mixes, are objective measures and are used to reflect the efficiency of manufacturing. Because the unit of measure of simulation data can range from number of lots to hours and to dollars, we need to transform these quantitative data 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 at level 3 is as follows [7]:

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

X_m^+: The best value of detailed criteria m at level 3.
X_m^-: The worst value of detailed criteria m at level 3.
X: The value of detailed criteria m under a certain product mix.

Table 5. Comparison matrix and eigenvector for *product*

Product	WIP	TP	TL	CT	Relative importance weights (eigenvector, w_{2P})
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

$CR = 0.07$

Table 6. Comparison matrix and eigenvector for *equipment efficiency*

Equipment efficiency	BU	CU	Eigenvector, w_{2E}
BU	1	9	0.900
CU	1/9	1	0.100

$CR = 0.00$

Table 7. Comparison matrix and eigenvector for *finance*

Finance	TR	VC	Eigenvector, w_{2F}
TR	1	6	0.857
VC	1/6	1	0.143

$CR = 0.00$

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*), we prefer their values to be as great as possible, and thus the best factors have the greatest values, and vice versa. On the other hand, for other detailed criteria (*WIP*, *total cycle time* and *variable costs*), their values are preferred to be small, and therefore the best ones are those with the smallest values. The simulation results in Table 2 are transformed into utility indices as shown in Table 8. The utility indices are then transformed into weights by dividing each utility index by the total value of the column, and the results that have the same upper level criteria are grouped together to be $\boldsymbol{W}_{3P}$, $\boldsymbol{W}_{3E}$ and $\boldsymbol{W}_{3E}$, as shown in Tables 9 to 11.

Finally, the overall priorities for the product mixes are obtained by the following formula:

$$w^{\mathrm{AHP}} = \begin{bmatrix} \boldsymbol{W}_{3P} \times w_{2P}, & \boldsymbol{W}_{3E} \times w_{2E}, & \boldsymbol{W}_{3F} \times w_{2F} \end{bmatrix} \times w_1$$

$$= \begin{bmatrix} 0.086177 & 0.1156 & 0.148153 \\ 0.090815 & 0.1146 & 0.156140 \\ 0.099202 & 0.1136 & 0.146995 \\ 0.110431 & 0.1126 & 0.120432 \\ 0.118908 & 0.1107 & 0.101293 \\ 0.120284 & 0.1097 & 0.096430 \\ 0.124043 & 0.1087 & 0.082287 \\ 0.123891 & 0.1077 & 0.082706 \\ 0.126098 & 0.1058 & 0.066564 \end{bmatrix} \times \begin{bmatrix} 0.258 \\ 0.105 \\ 0.637 \end{bmatrix}$$

$$= \begin{array}{c} \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IV} \end{array} \begin{bmatrix} 0.129 \\ 0.135 \\ 0.131 \\ 0.117 \\ 0.107 \\ 0.104 \\ 0.095 \\ 0.096 \\ 0.086 \end{bmatrix}$$

If the AHP approach is employed, alternative II, product mix (2:8), can lead to efficient manufacturing with a relative importance value of 0.135, followed by alternative III, product mix (3:7), with a relative importance value of 0.131. The third most efficient product mix is alternative I, product mix (1:9), with a value of 0.129. However, there seems to be a trend of decreasing efficiency as the ratio of product A increases.

8 ANP for product mix determination

In this section, a simplified ANP approach, which is introduced in Sect. 4, is adopted. Here we take into consideration the interrelationship among detailed criteria with respect to an upper level criterion (i.e., product, equipment efficiency and finance). Note that the basic pairwise comparisons and simulation results are the same as those of AHP. The procedures are as follows:

Step 1: Determine the importance of each decision criteria with respect to achieving the overall objective, the efficient manufacturing performance. The results are the same as shown in Table 4, and

$$w_1 = \begin{array}{c} P \\ E \\ F \end{array} \begin{bmatrix} 0.258 \\ 0.105 \\ 0.637 \end{bmatrix} .$$

Step 2: Assuming there is no interdependence among detailed criteria, which detailed criteria should be emphasized more in determining their respective upper level criterion? The results are the same as in Tables 5 to 7, and the eigenvectors w_{2P}, w_{2E} and w_{2F} are:

$$w_{2P} = \begin{array}{c} WIP \\ TP \\ TL \\ CT \end{array} \begin{bmatrix} 0.134 \\ 0.284 \\ 0.499 \\ 0.083 \end{bmatrix} , \quad w_{2E} = \begin{array}{c} BU \\ CU \end{array} \begin{bmatrix} 0.900 \\ 0.100 \end{bmatrix}$$

$$\text{and} \quad w_{2F} = \begin{array}{c} TR \\ VC \end{array} \begin{bmatrix} 0.857 \\ 0.143 \end{bmatrix} .$$

Table 8. Utility index of each detailed criteria under different product mixes

Alternative	WIP	Throughput (TP)	Total layers (TL)	Total cycle time (CT)	BN utilization (BU)	CCR utilization (CU)	Total revenue (TR)	Variable costs (VC)
I	0.511	0.5	0.44	0.0525	1	0.8	0.1290323	0.58466
II	0.278	0.56	0.4975	0.13975	1	0.75	0.1489401	0.388335
III	0.368	0.6	0.514	0.26275	1	0.7	0.1419355	0.326465
IV	0.727	0.62	0.4905	0.40775	1	0.65	0.1091244	0.39529
V	0.878	0.65	0.485	0.58025	1	0.55	0.0875576	0.40441
VI	0.717	0.7	0.516	0.5885	1	0.5	0.0884793	0.294135
VII	0.684	0.74	0.5265	0.66825	1	0.45	0.0759447	0.25109
VIII	0.362	0.8	0.572	0.7165	1	0.4	0.0847926	0.09241
IX	0.303	0.84	0.579	0.78425	1	0.3	0.0689401	0.06066
Sum of column	4.828	6.01	4.6205	4.2005	9	5.1	0.9347465	2.797455

Table 9. Utility weight of detailed criteria with respect to *product* under different product mixes, $\boldsymbol{W}_{3P}$

$\boldsymbol{W}_{3P}$	WIP	TP	TL	CT
I	0.106	0.083	0.095	0.012
II	0.058	0.093	0.108	0.033
III	0.076	0.100	0.111	0.063
IV	0.151	0.103	0.106	0.097
V	0.182	0.108	0.105	0.138
VI	0.148	0.116	0.112	0.140
VII	0.142	0.123	0.114	0.159
VIII	0.075	0.133	0.124	0.171
IX	0.063	0.140	0.125	0.187

Table 10. Utility weight of detailed criteria with respect to *equipment efficiency* under different product mixes, $\boldsymbol{W}_{3E}$

$\boldsymbol{W}_{3E}$	BU	CU
I	0.111	0.157
II	0.111	0.147
III	0.111	0.137
IV	0.111	0.127
V	0.111	0.108
VI	0.111	0.098
VII	0.111	0.088
VIII	0.111	0.078
IX	0.111	0.059

Table 11. Utility weight of detailed criteria with respect to *finance* under different product mixes, $\boldsymbol{W}_{3F}$

$\boldsymbol{W}_{3F}$	TR	VC
I	0.138	0.209
II	0.159	0.139
III	0.152	0.117
IV	0.117	0.141
V	0.094	0.145
VI	0.095	0.105
VII	0.081	0.09
VIII	0.091	0.033
IX	0.074	0.022

Step 3: Since there is no interdependence among alternatives (product mix), they are compared with respect to each detailed criterion yielding the column eigenvectors regarding each detailed criterion. These data are obtained from the transformation of simulation results and the same as for the AHP analysis in Tables 9 to 11 in the previous section. Three matrices $\boldsymbol{W}_{3\mathrm{P}}$, $\boldsymbol{W}_{3\mathrm{E}}$ and $\boldsymbol{W}_{3\mathrm{F}}$ are restated here.

$$\boldsymbol{W}_{3\mathrm{P}} = \begin{array}{c} \\ \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{array}{c} \begin{array}{cccc} WP & TP & TL & CT \end{array} \\ \begin{bmatrix} 0.106 & 0.083 & 0.095 & 0.012 \\ 0.058 & 0.093 & 0.108 & 0.033 \\ 0.076 & 0.100 & 0.111 & 0.063 \\ 0.151 & 0.103 & 0.106 & 0.097 \\ 0.182 & 0.108 & 0.105 & 0.138 \\ 0.148 & 0.116 & 0.112 & 0.140 \\ 0.142 & 0.123 & 0.114 & 0.159 \\ 0.075 & 0.133 & 0.124 & 0.171 \\ 0.063 & 0.140 & 0.125 & 0.187 \end{bmatrix} \end{array}$$

$$\boldsymbol{W}_{3E} = \begin{array}{c} \\ \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{array}{c} \begin{array}{cc} BU & CU \end{array} \\ \begin{bmatrix} 0.111 & 0.157 \\ 0.111 & 0.147 \\ 0.111 & 0.137 \\ 0.111 & 0.127 \\ 0.111 & 0.108 \\ 0.111 & 0.098 \\ 0.111 & 0.088 \\ 0.111 & 0.078 \\ 0.111 & 0.059 \end{bmatrix} \end{array},$$

$$\boldsymbol{W}_{3\mathrm{F}} = \begin{array}{c} \\ \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{array}{c} \begin{array}{cc} TR & VC \end{array} \\ \begin{bmatrix} 0.138 & 0.209 \\ 0.159 & 0.139 \\ 0.152 & 0.117 \\ 0.117 & 0.141 \\ 0.094 & 0.145 \\ 0.095 & 0.105 \\ 0.081 & 0.090 \\ 0.091 & 0.033 \\ 0.074 & 0.022 \end{bmatrix} \end{array}.$$

Step 4: Analyse the interdependence among the detailed criteria. Correlation analysis is performed, and the values are normalized so that the sum of each column is one. The interdependence weight matrices of detailed criteria with the same upper level criterion are as in Tables 12 to 13.

Step 5: Obtain the interdependence priorities of the detailed criteria by synthesizing the results from Step 2 and Step 4. $w_{DC(n)} = \mathbf{W}_{4n} \times w_{2n}$ for $n = P, E, F$

$$w_{DC(P)} = \mathbf{W}_{4P} \times w_{2P}$$

$$= \begin{array}{ccccc} & WP & TP & TL & CT \\ WP & 1.000 & 0.004 & 0.000 & 0.020 \\ TP & 0.000 & 0.518 & 0.458 & 0.470 \\ TL & 0.000 & 0.000 & 0.542 & 0.000 \\ CT & 0.000 & 0.478 & 0.000 & 0.510 \end{array}$$

$$\times \begin{array}{cc} WP & 0.134 \\ TP & 0.284 \\ TL & 0.499 \\ CT & 0.083 \end{array}$$

$$= \begin{array}{cc} WP & 0.137 \\ TP & 0.415 \\ TL & 0.270 \\ CT & 0.178 \end{array}$$

$$w_{DC(E)} = \mathbf{W}_{4E} \times w_{2E}$$

$$= \begin{array}{ccc} & BU & CU \\ BU & 1.000 & 0.458 \\ CU & 0.000 & 0.542 \end{array} \times \begin{array}{cc} BU & 0.900 \\ CU & 0.100 \end{array}$$

$$= \begin{array}{cc} BU & 0.946 \\ CU & 0.054 \end{array}$$

$$w_{DC(F)} = \mathbf{W}_{4F} \times w_{2F}$$

$$= \begin{array}{ccc} & TR & VC \\ TR & 0.558 & 0.442 \\ VC & 0.442 & 0.558 \end{array} \times \begin{array}{cc} TR & 0.857 \\ VC & 0.143 \end{array}$$

$$= \begin{array}{cc} TR & 0.541 \\ VC & 0.459 \end{array}$$

Table 12. Interdependence matrix of detailed criteria with respect to *product*

$\mathbf{W}_{4P}$	WIP	TP	TL	CT
WIP	1.000	0.004	0.000	0.020
TP	0.000	0.518	0.458	0.470
TL	0.000	0.000	0.542	0.000
CT	0.000	0.478	0.000	0.510
Sum	1.000	1.000	1.000	1.000

Table 13. Interdependence matrix of detailed criteria with respect to *equipment efficiency*

$\mathbf{W}_{4E}$	BU	CU
BU	1	0.458
CU	0	0.542
Sum	1.000	1.000

Table 14. Interdependence matrix of detailed criteria with respect to *finance*

$\mathbf{W}_{4F}$	TR	VC
TR	0.558	0.442
VC	0.442	0.558
Sum	1.000	1.000

Step 6: The priorities of alternatives with respect to each of the three criteria are given by synthesizing the results from Step 3 and Step 5 as follows: $w_{21(n)} = \mathbf{W}_{3n} \times w_{DC(n)}$ for $n = P, E, F$

$$w_{21(P)} = \mathbf{W}_{3P} \times w_{DC(P)}$$

$$= \begin{array}{ccccc} & WP & TP & TL & CT \\ \text{I} & 0.106 & 0.083 & 0.095 & 0.012 \\ \text{II} & 0.058 & 0.093 & 0.108 & 0.033 \\ \text{III} & 0.076 & 0.100 & 0.111 & 0.063 \\ \text{IV} & 0.151 & 0.103 & 0.106 & 0.097 \\ \text{V} & 0.182 & 0.108 & 0.105 & 0.138 \\ \text{VI} & 0.148 & 0.116 & 0.112 & 0.140 \\ \text{VII} & 0.142 & 0.123 & 0.114 & 0.159 \\ \text{VIII} & 0.075 & 0.133 & 0.124 & 0.171 \\ \text{IX} & 0.063 & 0.140 & 0.125 & 0.187 \end{array}$$

$$\times \begin{array}{cc} WP & 0.137 \\ TP & 0.415 \\ TL & 0.270 \\ CT & 0.178 \end{array}$$

$$= \begin{array}{cc} \text{I} & 0.077 \\ \text{II} & 0.082 \\ \text{III} & 0.093 \\ \text{IV} & 0.109 \\ \text{V} & 0.123 \\ \text{VI} & 0.124 \\ \text{VII} & 0.130 \\ \text{VIII} & 0.129 \\ \text{IX} & 0.134 \end{array}$$

$$w_{21(E)} = \mathbf{W}_{3E} \times w_{DC(E)}$$

$$= \begin{array}{ccc} & BU & CU \\ \text{I} & 0.111 & 0.157 \\ \text{II} & 0.111 & 0.147 \\ \text{III} & 0.111 & 0.137 \\ \text{IV} & 0.111 & 0.127 \\ \text{V} & 0.111 & 0.108 \\ \text{VI} & 0.111 & 0.098 \\ \text{VII} & 0.111 & 0.088 \\ \text{VIII} & 0.111 & 0.078 \\ \text{IX} & 0.111 & 0.059 \end{array} \times \begin{array}{cc} BU & 0.954 \\ CU & 0.046 \end{array}$$

$$= \begin{array}{cc} \text{I} & 0.113 \\ \text{II} & 0.113 \\ \text{III} & 0.112 \\ \text{IV} & 0.112 \\ \text{V} & 0.111 \\ \text{VI} & 0.110 \\ \text{VII} & 0.110 \\ \text{VIII} & 0.109 \\ \text{IX} & 0.108 \end{array}$$

$$w_{21(F)} = \boldsymbol{W}_{3F} \times w_{DC(F)}$$

$$= \begin{array}{c} \\ \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{array}{c} \begin{array}{cc} TR & VC \end{array} \\ \begin{bmatrix} 0.138 & 0.209 \\ 0.159 & 0.139 \\ 0.152 & 0.117 \\ 0.117 & 0.141 \\ 0.094 & 0.145 \\ 0.095 & 0.105 \\ 0.081 & 0.090 \\ 0.091 & 0.033 \\ 0.074 & 0.022 \end{bmatrix} \end{array} \times \begin{array}{c} TR \\ VC \end{array} \begin{bmatrix} 0.558 \\ 0.442 \end{bmatrix}$$

$$= \begin{array}{c} \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{bmatrix} 0.169 \\ 0.150 \\ 0.137 \\ 0.128 \\ 0.117 \\ 0.099 \\ 0.085 \\ 0.065 \\ 0.051 \end{bmatrix}$$

We define the matrix $\boldsymbol{W}_{21}$ by grouping together the above three columns: $\boldsymbol{W}_{21} = \left(w_{21(P)}, w_{21(E)}, w_{21(F)}\right)$

$$\boldsymbol{W}_{21} = \begin{array}{c} \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{bmatrix} 0.077 & 0.113 & 0.169 \\ 0.082 & 0.113 & 0.150 \\ 0.093 & 0.112 & 0.137 \\ 0.109 & 0.112 & 0.128 \\ 0.123 & 0.111 & 0.117 \\ 0.124 & 0.110 & 0.099 \\ 0.130 & 0.110 & 0.085 \\ 0.129 & 0.109 & 0.065 \\ 0.134 & 0.108 & 0.051 \end{bmatrix}$$

Step 7: The overall priorities for the alternatives (product mixes) are obtained by synthesizing the results from Step 1 and Step 6. That is, they are calculated by multiplying $\boldsymbol{W_{21}}$ by w_1.

$$w^{ANP} = \boldsymbol{W}_{21} \times w_1$$

$$= \begin{array}{c} \\ \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{array}{c} \begin{array}{ccc} P & E & F \end{array} \\ \begin{bmatrix} 0.077 & 0.113 & 0.169 \\ 0.082 & 0.113 & 0.150 \\ 0.093 & 0.112 & 0.137 \\ 0.109 & 0.112 & 0.128 \\ 0.123 & 0.111 & 0.117 \\ 0.124 & 0.110 & 0.099 \\ 0.130 & 0.110 & 0.085 \\ 0.129 & 0.109 & 0.065 \\ 0.134 & 0.108 & 0.051 \end{bmatrix} \end{array} \times \begin{array}{c} P \\ E \\ F \end{array} \begin{bmatrix} 0.258 \\ 0.105 \\ 0.637 \end{bmatrix}$$

$$= \begin{array}{c} \mathrm{I} \\ \mathrm{II} \\ \mathrm{III} \\ \mathrm{IV} \\ \mathrm{V} \\ \mathrm{VI} \\ \mathrm{VII} \\ \mathrm{VIII} \\ \mathrm{IX} \end{array} \begin{bmatrix} 0.140 \\ 0.129 \\ 0.123 \\ 0.121 \\ 0.118 \\ 0.107 \\ 0.099 \\ 0.086 \\ 0.078 \end{bmatrix}$$

The ANP analysis results indicate that the most efficient manufacturing is alternative I, product mix (1:9), with a relative importance value of 0.140, which is slightly more important than alternative II, product mix (2:8), with a value of 0.129. The ranking of the product mixes is exactly the descending order from alternative I to IV, that is, from product mix (1:9) to (9:1). This implies that Product B is highly recommended for manufacturing.

If the AHP approach is employed, alternative II appears as the most efficient product mix with a relative importance value of 0.135, followed by alternative III with a relative importance value of 0.131, and alternative I with a value of 0.129. However, when interdependencies of detailed criteria are incorporated into the analysis by applying the simplified ANP approach, alternative II declines to the second place with relative value of 0.129 whereas alternative I, ranked third in AHP approach, ranks in the first place with a value of 0.140. Consequently, the ranking results of ANP are different from those of AHP. Incorporating the interdependencies among factors, the ANP approach is preferred to the AHP approach in the determination of efficient product mix.

The ranking order of ANP results is exactly from alternative I to IV, and this implies that product B is strongly advised to produce. Some trends can be found from the simulation results in Table 2 and the obtained eigenvectors. 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 B, which has a higher price than A, is produced. This applies until alternative I, with product mix (1:9), where *total layers*, *throughput* and *cycle time* are adversely affected. *Variable costs* also have a decreasing trend as a higher ratio of product B is produced. Since both *throughput* and *total layers* are less in the product mixes with a higher ratio of product B, *variable costs* are lower. With the above combination, product mixes with a higher ratio of product B are preferred. Other criteria (*product* and *equipment efficiency*), even though having some contribution weights, are not powerful enough to have a strong impact on the final ranking.

9 Conclusions

The selection of an appropriate product mix in a wafer fab is essential to achieve optimal manufacturing. This paper applied both AHP and ANP methods to evaluate the manufacturing performance under different product mixes in a semiconductor fabricator. Although the results of AHP and ANP do not show great disparity, there are some difference in ranking and the final priority weights of the alternatives. ANP, which considers the interrelationship among factors, should be adopted if possible. The results provide guidance for a fab in accepting orders when its capacity cannot fully satisfy all the product demand. A simplified ANP approach is used in this paper; however, a more complicated network of efficient product mix can be present in semiconductor manufacturing. How to organize a network problem and use the comprehensive ANP will be our future research direction. In addition, due to the intensive competition in the semiconductor industry, multiple priority orders, such as hot lots, rush lots and normal lots, are accepted in order to satisfy customer demand. As a result, the manufacturing environment can be very complex, and this can also be our future focus of research.

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