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ORIGINAL ARTICLE

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Outsourcing capacity planning for an an IC design house

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Abstract The management of outsourcing capacity is one of the key issues for IC design houses. There are two fundamental problems in outsourcing capacity management; they are the estimation of net capacity and the allocation of capacity. The purpose of this paper is to propose a framework of outsourcing capacity planning (OCP) for an IC design house to solve these two problems. The framework of OCP contains three parts: Net IC Product Demand Planning, Net Capacity Demand Planning, and Booking Capacity Planning. Linear Programming (LP) is employed to generate a net IC demand plan. A transformation process that transforms net IC product demand into net capacity demand is applied to obtain the net capacity demand plan. Finally, we use Analytic Hierarchy Process (AHP) to combine the factors, which an IC design house considers for outsourcing, into a Utility Index (U.I.). We then employ U.I. to develop a heuristic method to deal with the booking capacity planning problem. The result of OCP yields a better performance than that of the practice approach. In addition, OCP provides a decision procedure to assist IC design houses in monitoring the performance of each subcontractor.

Keywords IC design house · Outsourcing Capacity Planning · Booking Capacity Planning · Linear Programming · Analytic Hierarchy Process

1 Introduction

In the last decade, the semiconductor industry has become one of the world's booming industries. An IC design house plays an important role in the semiconductor industry because it creates and determines the demand of the semiconductor supply chain. An IC design house focuses on IC design as well as development. It outsources its manufacturing processes to downstream suppliers. Therefore, capacity planning for an IC design house depends on the capacity that the downstream suppliers, also called subcontractors, can provide. Management of the outsourcing capacity is an important task for an IC design house.

There are two fundamental issues in outsourcing capacity management: the estimation of net capacity demand and the allocation of the capacity. They both have a direct impact on the production management and on the ability to respond to customer requests and needs. However, past studies [1, 2, 3] focused on MPS, MRP and shop flow control. Few have focused on the abovementioned two issues.

The purpose of this paper is to propose a mechanism of outsourcing capacity planning (OCP) to solve both capacity estimation and capacity allocation problems for an IC design house. Both liner programming and transformation process are employed to tackle the estimation problem. A heuristic method with a utility index used in AHP is proposed to deal with the allocation problem.

The organization of this paper is as follows. Section 2 presents related studies about an IC design house. Section 3 introduces the methodology for solving both estimation and allocation capacity problems. In Section 4, an example as well as the numerical results are discussed. Section 5 is the conclusion.

2 Related studies for an IC design house

A fabless and an integrated device manufacturer (IDM) are the two main classes of an IC design house. The Fabless Semiconductor Association (FSA) [4] defines these two classes below.

Fabless (without a fab) refers to the business methodology of outsourcing the manufacturing of silicon

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wafers, which hundreds of semiconductor companies have adopted. Fabless companies focus on the design, development and marketing of their products and form alliances with silicon wafer manufacturers, or foundries.

Integrated Device Manufacturer (IDM) is a class of semiconductor company, which owns an internal silicon wafer fab, or, as the name indicates, the fabrication of wafers is integrated into its business. However, even IDMs may do some outsourcing.

According to the definitions of the FSA, the business models of the two classes are different. Dhayagude et al. [5] showed the differences of business models between them in Fig. 1.

Because all manufacturing of Fabless is outsourced, the Fabless company will find outsourcing capacity management especially important. The quality of the outsourcing capacity management determines the production flexibility and the time-to-market capability. In this research, we focus on the Fabless company and study the corresponding outsourcing capacity problem. Figure 2 shows the scheme of the semiconductor industry.

Most production planning studies about an IC design house focus on MPS, MRP and shop floor control. Leachman is one of the pioneers who developed a production planning model for IDM. Leachman [7] divided the planning problem of IDM into three levels: strategic planning, corporate planning and factory floor scheduling and control. He proposed a linear optimal model for a global production planning system that was applied to the Harris Corporation-Semiconductor Sector, called the integrated manufacturing production requirements scheduling system (IMPReSS) [8].

Lin et al. [2] presented P (Production) and M (Market) capacity models to solve the production planning problem. These models were based on the concept of maximum production under the constraint of the satisfaction of marketing requirements. Chen [1] presented a framework of production planning and control for an IC design house and split this framework into three steps: capacity planning, capacity assignment and shop floor control.

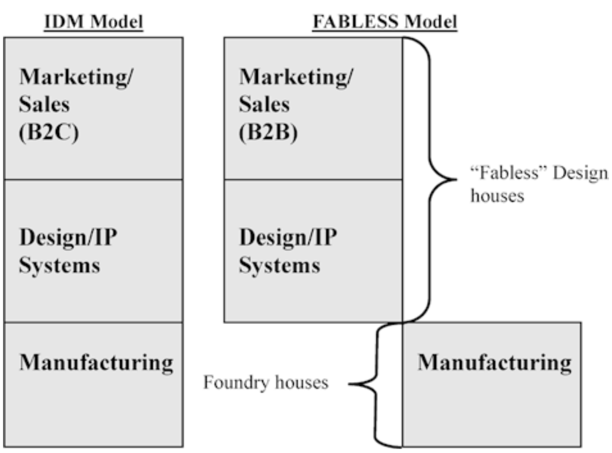


Fig. 1 The business models of IDM and Fabless, respectively [5]

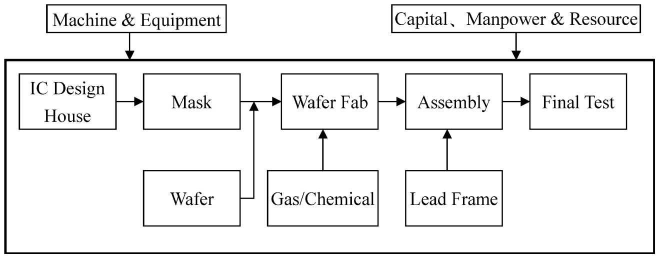


Fig. 2. A scheme of the semiconductor industry [6]

Lin et al. [9] proposed a mechanism to generate an ideal schedule for the releasing and finishing time in each outsourcing plant under the capacity and cycle time constraints. Fang [3] took the capacity status, the production cost, the production time and special machine constraints into consideration to develop a capacity model.

The abovementioned studies focused in general on short-term planning and made production plans assuming specific vendors' capacities, which resulted from the OCP output. However, OCP, an estimation of net outsourcing capacity and the allocation of the capacity, is a mid-term production planning issue. OCP determines the performance of the short-term production plan. There is little literature available for OCP. We, therefore, intend to propose a framework to solve this problem by using a linear programming model, a transformation process and a heuristic allocation approach.

3 Methodology

3.1 Problem definition

The planning horizon of OCP is often from three to six months. It is assumed that the planning horizon is six months in this research. Before the estimation of net capacity demand, we need to estimate net IC product demand and then transform the product demand to the capacity demand. For net product demand calculation, we assume that the IC product inventory, the sales forecasts and the WIP of each subcontractor are known.

There are three main problems of OCP to be solved in this research. The first is to estimate the net IC product demand. To transform the product demand to the capacity demand is the second issue. Finally, we need to decide how to allocate the capacity demand to the downstream subcontractors. In this paper, we propose a framework to solve these three problems, as shown in Fig. 3.

The framework of OCP has three components: net IC production planning, net capacity demand planning and booking capacity planning. They cope with the abovementioned three problems, respectively. Net IC product

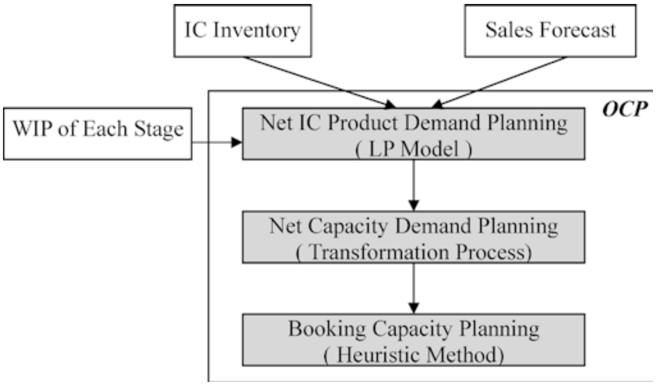


Fig. 3 The framework of OCP

demand planning applies an LP model to solve the net product demand problem. Net capacity demand planning deals with the net capacity demand problem through a transformation process. Booking capacity planning proposes a heuristic method to handle the allocation problem. These are discussed in detail from Section 3.2 to Section 3.4.

3.2 Net IC product demand planning

The special phenomenon—bin split, also called binning—makes the the estimation of the net IC product demand more difficult. Leachman [10] presented a simplified example of requirements planning including two bins and two finished goods, as shown in Fig. 4.

He showed that an IC design house usually tries to apply MRP logic to binning structures in two ways. One way is to directly sum up the requirements of the finished goods to find the input demand of the source product, ignoring the bin splits. The other method is to select a single bin as the "driver bin" as the base from which an IC design house conducts the requirement planning calculations. However, he found that in both ways, MRP logic cannot estimate the optimal input to satisfy customer demand. In addition, MRP logic doesn't consider the inventories of each bin in each period of dynamic demand.

Leachman et al. [8] referred requirement planning with binning to a classic multi-period model using linear programming. They proposed a multi-period and dynamic LP model to handle the binning problem. Lin et al. [9] compared LP with traditional methods and demonstrated that the performance of LP was superior.

However, the product structure of an IC design house is different from that presented by Leachman. Firstly, there is no interaction between the material fab and an IC design house. Wafer fab buys silicon wafers from material fab after it gets orders from an IC design house. An IC design house only controls four main procedures: wafer fab, wafer probe, assembly and final test.

Secondly, there is no bin inventory in the final test. The final test splits ICs into several bins and classifies bins into a few grades with the corresponding specifications of an IC design house. ICs are marked with grades and sent directly to an IC design house. An IC design house only has a finished goods inventory. If unplanned demands occur, an IC design house can respond to the demand using its finished goods inventory.

The planning horizon is another difference between this study and Leachman's research. The planning horizon of Leachman's multi-period LP was restricted to short-term planning, but that of our study extends the time interval to a moderately long time frame. The components of demands in our study and in Leachman's research are different. The demands of Leachman's LP model included orders, sales forecast and inventory replenishment. Demands of our research only include sales forecast (six months to one year) and firmed long-term orders. For simplicity, we compound the sales forecast and firmed orders into future demand in this research.

In addition, we label the products by one product group if the products have the same routing before the final test and only are separated during it. Leachman presented a rather simple bin split example. Both Bin 1 and Bin 2 belong to the same product group. We synthesised the above differences and considered transfer WIPs of each front stage (wafer fab, wafer probe, and assembly) to propose a net demand LP model as follows.

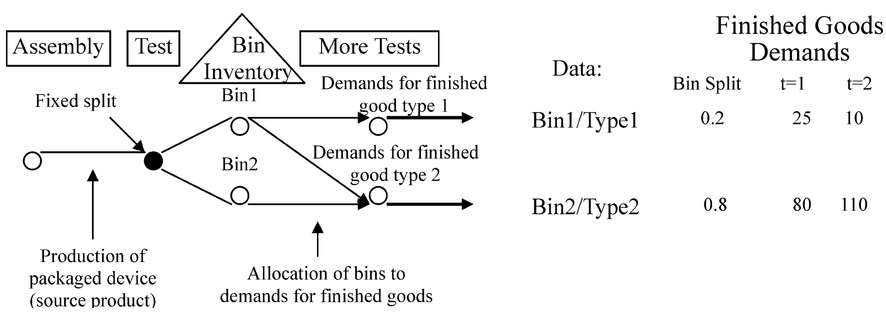
Objective function:

$$Min \sum_{i} \sum_{t} C_i X_{it} + \sum_{j} \sum_{t} H_j I_{jt}$$

Subject to:

(1) Production quantity $Y_{k(t+1)} = a_{ik}(x_{i4t} + X_{it})$, $\forall i = 1, 2, 3 \ldots n; t = 1, 2, 3 \ldots T - 1; k \in K_i$

Fig. 4 A requirement planning example with binning [10]



(2) Bin split allocation $\sum_{j\in\{j|K_j\supset k\}} Y_{kjt} = Y_{kt}, \forall k = 1,2\ldots K; t = 1,2,3\ldots T$

(3) Demand quantity $D_{jt} = I_{j(t-1)} + \sum_{k\in K_j} Y_{kjt} - I_{jt}$, $\forall j = 1,2,3\ldots N; t = 2,3,4\ldots T$

(4) Transfer WIP

Wafer fab: $\alpha_{i1}x_{i1t} = x_{i2(t+4)} \forall i = 1,2,3\ldots n$; $t = 1,2,3\ldots T-4$

Wafer probe: $\alpha_{i2}x_{i2t} = x_{i3(t+1)} \forall i = 1,2,3\ldots n$; $t = 1,2,3\ldots T-1$

Assembly: $\alpha_{i3}x_{i3t} = x_{i4(t+1)} \forall i = 1,2,3\ldots n$; $t = 1,2,3\ldots T-1$

(5) Nonnegative $X_{it}, I_{jt}, x_{ipt}, Y_{kt} Y_{kjt}, D_{jt} \geqslant 0 \forall i, j, c, t$

Parameter:

i: product group, $i = 1,2,3...n$

j: product type, $j = 1,2,3...N$

t: period, $t = 1,2,3...T$, one period is one week

k: Bin, $k = 1,2,3...K$

p: main production stage, $p = 1,2,3,4$;

K_i: :the set of Bins that belong to product group i

K_j: :the set of Bins which product type j can use

C_i: :unit production cost of product group i in the final test

H_j: :holding cost of product type j

a_{ik}: :the bin split of Bin k of product group i

a_{ip}: :yield of product group i at stage p

Variables:

X_{it}: :the net demand input of product group i at Final test in period t

I_{jt}: :the inventory of product type j in period t

x_{ipt}: :WIP input of product group i at stage p in period t

Y_{kt}: :the throughput of Bin k in period t

Y_{kjt}: :the quantity of Bin k to assign to product type j in period t

D_{jt}: :the demand of product type j in period t

The objective function is to minimise the sum of the production cost and the holding cost in the final test while corresponding with the following constraints. Constraint 1 implies the WIP plus the net input in the current period is equal to the throughput of Bin k in the next period. Constraint 2 demonstrates that the throughput of Bin k is equal to the sum of Bin k which is allocated to certain product types in period t. Constraint 3 defines the current demand for each product as the beginning inventory plus the allocation quantity in the current period minus ending inventory. Constraint 4 calculates transfer of the WIP of each stage for estimating the projected WIP in the final test. Constraint 5 presents the nonnegative restrictions.

3.3 Net capacity demand planning

To transform product demand into capacity demand, we present the booking capacity unit and the booking period used at different outsourced stages in Table 1. In this research, we assume that the capacity unit for wafer fabs and wafer probes is a piece of wafer, and the capacity unit for the assembly and the final test is a die.

Table 1 The capacity unit and the period of booking capacity

Stage	Wafer fab	Wafer probe	Assembly	Final test
Period	Month	Month	Month	Month
Product structure	Piece	Piece	Die	Die
Capacity unit	Piece	Piece/hour	Die	Die/hour

Estimations of the capacity demand in the four main outsourced stages decides the net capacity demand at each stage. According to Table 1, the net input demand of the final test can be taken directly as the throughput of the assembly. However, we need to consider the yield of the final test to transform the input schedule of the final test into the output schedule of the assembly. (Tables 2 and 3).

After getting the output schedule of the assembly, we can do forward and backward arrangement of the output schedule for wafer fab, the wafer probe and the final test by using both the standard cycle time and the average yield of each stage in Fig. 5.

Generally speaking, the an IC design house determines the due date of orders at each stage by a standard cycle time. If subcontractors cannot make the predetermined due date, the IC design house may transfer this order to another subcontractor for time-to-market consideration. We used the standard cycle time for forward and backward scheduling in our study. After calculating the output schedule for each stage, we can summarise total capacity demand by month to create net capacity demand plans. (Table 4)

3.4 Booking capacity planning (BCP)

3.4.1 Booking capacity scenario

Complex production characteristics of the semiconductor industry increase the difficulty of BCP. Generally, a few special ICs would only be made in specialised factories due to certain requirements such as manufacturing technology, yield, and so on. The capacity demand of this kind of IC must be assigned to specific subcontractors. This phenomenon occurs at each stage. Other particular features of each stage are discussed as follows.

Table 2 The input schedule of the final test (Unit: Thousand Dies)

Period	Quantity	Period	Quantity
1	0	7	50
2	55	8	60
3	0	9	0
4	0	10	53.75
5	75	11	62.5
6	50		

Table 3 The output schedule of the assembly (the yield of the final test = 0.92; Unit: Thousand Dies)

Period	Quantity	Period	Quantity
1	0	7	54.35
2	59.78	8	65.22
3	0	9	0
4	0	10	58.42
5	81.52	11	67.93
6	54.35		

Table 4 The bet capacity demand plan (Unit: Thousand Dies)

Month	Wafer fab	Probe	Assembly	Final test
1	148.65	61.63	59.78	55
2	182.95	263.33	255.44	175
3	132.93	130.27	126.35	176.25

IC design houses generally put a great deal of emphasis on the selection and control of wafer fabs, especially in technology and yield, because wafer fabs affect the performance of the following outsourced manufacturing stages. 0.18 μ and 0.25 μ process technologies are the current two main technologies and decide the die quantity of a wafer. Without a loss of generality, this research assumes 0.18 μ and 0.25 μ are the only process technologies. The capacity demand of the wafer fab needs to be split into these two types to aid the capacity allocation.

In addition to the process technology, the wafer size of the wafer fabs is another factor that would affect production cost. In general, the wafer size of the wafer fabs can be divided into three classes: 6-inch, 8-inch and 12-inch. 6-inch wafer fabs have a gradually declining market and 12-inch are not popular for mass production. Therefore, we assume 8-inch to be the only wafer size in this research.

When an IC design house books the capacity of wafer fabs, it usually books the capacity demand of the wafer probe at the same time because the cycle time of the wafer probe is much shorter and most wafer fabs provide both wafer fabs and wafer probes in the same manufacturing site. Therefore, we treat the wafer probe as a part of the wafer fab and do not further discuss this stage in this research.

There are more selections in the assembly. This makes capacity allocation difficult. Generally speaking, there are combinations of four features in the packaging process. These are package type, pin count, body size and pad size. However, package type and pin count are usually prescribed features, such as TSOP, SOJ and BGA or 16, 8 and 4 pin. After an IC design house finishes the new product development, the package type and pin count of the product are already appointed. Therefore, this research considers package type an addendum to booking capacity demand in order to simplify the allocation problem.

In the final test, an IC design house needs to select specific vendors with advanced manufacturing technology. Owing to the different testing ability of each subcontractor, an IC design house assigns specific ICs to the final test subcontractors who are able to test this IC. This situation is similar to that of selecting specific machines in the traditional manufacturing process, and we call this subcontractor selection.

Synthetically speaking, complicated status makes a mathematic model formulation difficult. We propose a utility index to solve the capacity allocation problem in the next section.

3.4.2 The utility index (UI)

Many factors, such as relationship, cost and manufacturing ability, need to be considered in BCP. An IC design house uses those factors to make an allocation decision. However, each factor presents only one feature of a subcontractor. We combine those factors into a utility index and use the index to calculate the overall performance of each subcontractor.

Combining those factors is a multiple criteria decision making (MCDM) problem. It is achieved by using an MCDM method. The analytic hierarchy process (AHP) developed by Thomas L. Saaty [11] is one of the MCDM methods. It has been widely used [12]. Jin et al. [13] pointed out that AHP provides the hierarchical structure to identify the different attributes and standardises relative importance rate among the attributes. Muralidhar et al. [14] indicated that AHP is easy to use and implement. Therefore, we apply AHP to consolidate those factors that an IC design house considers.

Firstly, we construct a hierarchical framework of factors, and then we decide the weighted values of those factors by the pairwise comparisons proposed in AHP. The framework and definition of those factors are discussed as follows (Fig. 6).

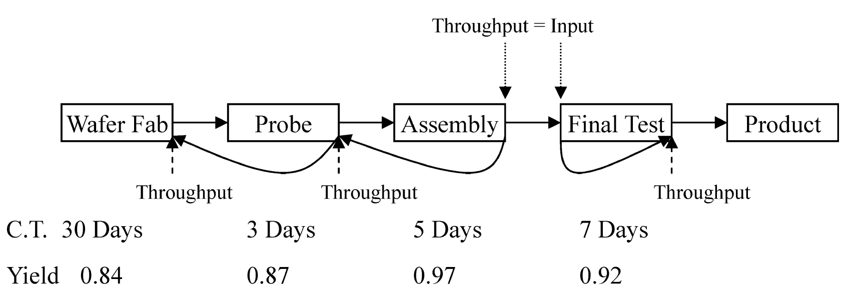


Fig. 5 The forward and backward scheduling process

3.4.3 *Definition*

Management criterion:

- Relationship: the correlation between an IC design house and a subcontractor.
- Accommodation: the adaptability of a subcontractor as an IC design house changes its demand.
- - Supply capacity: the capacity a subcontractor can provide.
- Specific actory: a specific subcontractor who has the technology or capability to produce a specific type of IC.

Technology Criterion:

- Manufacturing ability: an important index of technical ability that a company develops for an advanced manufacturing process.
- Quality variance: the variance of yield for a subcontractor.
- Fulfil rate: the ratio that orders are delivered on time.
- Lead time: the cycle time of a subcontractor.

Cost criterion:

- Production cost: unit production cost for a subcontractor.
- Quality loss cost: a cost that involves relative activities to handle the failed dies.
- Management cost: a cost caused by relative management activities, such as control, negotiation, adjustment, tracing and so forth.
- Customer loss cost: an opportunity cost with regards to thoroughness and time-to-market. Owing to the delay of output scheduling in the wafer fab, the cycle times of the assembly and the final test usually are shortened to keep better on-time-delivery and time-to-market performance. Therefore, this will only occur in the assembly and the final test.

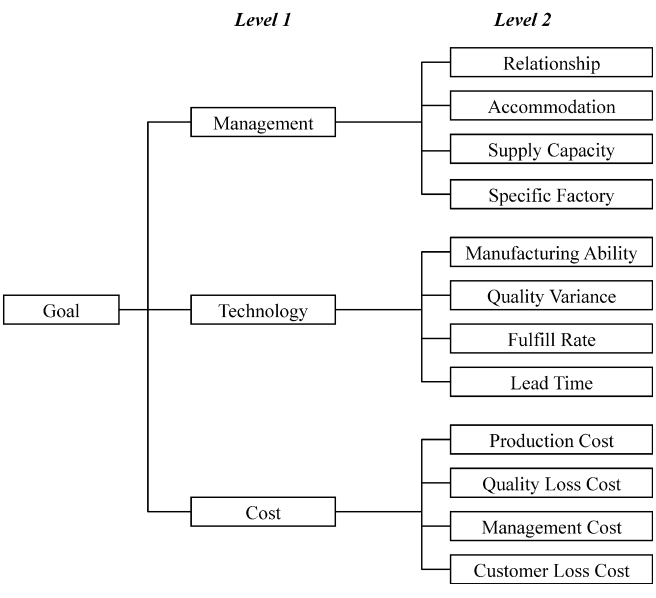


Fig. 6 The hierarchical framework of factors

In pairwise comparisons, AHP forces the decision maker to provide judgments about the relative importance for each factor. AHP employs an underlying scale with values 1–9 to rate the relative preferences for two items. Table 5 indicates the numerical ratings recommended for the verbal preferences that are expressed by the decision maker.

After pairwise comparisons, the next procedure is the synthesisation of AHP to compute eigenvalues and eigenvectors. The following three-step procedure shows a good approximation of the synthesised priorities [15].

3.4.4 *Synthesisation [15]*

Step 1: Sum the values in each column of the pairwise comparison matrix.

Step 2: Divide each element in the pairwise comparison matrix by its column total; the resulting matrix is referred to as the normalised pairwise comparison matrix.

Step 3: Compute the average of the elements in each row of the normalised matrix; these averages provide an estimate of the relative priorities of the elements being compared.

In terms of the ultimate decision, an important consideration is the consistency of the decision maker's judgments during the procedure of pairwise comparisons. AHP offers a measure of the consistency in pairwise comparison judgments by computing a consistency ratio as follows.

3.4.5 *Consistency [15]*

Step 1: Multiply each value in the first column of the pairwise comparison matrix by the relative priority of the first item considered; multiply each value in the second column of the matrix by the relative priority of the second item considered; until all items are done. Sum the values across the rows to obtain a vector of values labelled "weighted sum".

Table 5 The pairwise comparison scale for AHP preferences [11]

Verbal judgment of preference	Numerical rating
Extremely preferred	9
Very strongly to extremely	8
Very strongly preferred	7
Strongly to very strongly	6
Strongly preferred	5
Moderately to strongly	4
Moderately preferred	3
Equally to moderately	2
Equally preferred	1

Step 2: Divide the elements of the vector of weighted sums obtained in Step 1 by the corresponding priority value.

Step 3: Compute the average of the values found in Step 2; this average is denoted $\lambda_{\max}$.

Step 4: Compute the consistency index (CI), which is defined as $CI=(\lambda_{\max}-n)/(n-1)$

Step 5: Compute the consistency ratio (CR), which is defined as $CR=CI/RI$. The random index (RI), is the consistency index of a randomly generated pairwise comparison matrix. The RI, which depends on the number of elements being compared, takes on the values shown in Table 6. (Table 7 shows the characteristics of each factor). As mentioned previously, a consistency ration of 0.1 or less is considered acceptable [15].

After getting the weighted value of each factor, we still need the utility function of each factor to obtain a utility index and to show the performance of each subcontractor. For simplicity, we use the additive utility function to construct the utility value of each factor at level 2. The proportional scores method of the additive utility function is adopted in order to easily define utility value of each factor. The qualitative factors are measured by a nine-point scale, since the scale is higher when the performance is better. The measures of the quantitative factors are provided by each subcontractor and the binary factor is set by the IC specification.

The formula of utility function and characteristics of each factor are presented as follows.

3.4.6 Proportional Scores Method

$$u_i(x) = \frac{x - x_i^-}{x_i^+ - x_i^-}$$

Table 6 Random index [11]

n	3	4	5	6	7	8
RI	0.58	0.90	1.12	1.24	1.32	1.41

$u_i(x)$: The utility function of factor i at level 2

x_i^+: The best value of factor i at level 2

x_i^-: The worst value of factor i at level 2

The final step is to formulate the UI and to compute the value of the UI for each subcontractor. The UI formula for each subcontractor is given below.

$$U_k = \sum_i \sum_j w_i \times w_{ij} \times u_{ijk}$$

U_k: The value of U.I. for subcontractor k

w_i: The weight of criterion i at level 1

w_{ij}: The weight of factor j at level 2 under criterion i

u_{ijk}: The utility value of factor j at level 2 under criterion i for subcontractor k

Using the U.I., we can identify the performance of each subcontractor and conduct the booking capacity planning.

3.4.7 Heuristic booking capacity planning (HBCP)

Since it is not easy to formulate a mathematic model to handle the complex booking capacity problem, we propose a heuristic method with the utility index to solve this issue. It is called the HBCP. The detailed process is described in Fig 7.

Step 1: Check whether special ICs need to be made in a specific factory. If they do, the capacity demand of these ICs should be assigned to specific subcontractors first. If they are not, go to the next step.

Step 2: Set $i=1$. Capacity allocation starts from capacity demand type i.

Step 3: Set the priority of each subcontractor by the capacity demand type i that can be produced. We use the UI to set priorities for subcontractors: the subcontractor with the highest value of the UI has the highest priority. If there are subcontractors with the same utility value, they will be compared by the sum of the

Table 7 The characteristics of each factor

Level 1	Level 2	Attribute	Unit
Management	Relationship	Qualitative	Scale point
	Accommodation	Qualitative	Scale point
	Supply capacity	Quantitative	Piece or die
	Specific factory	Binary	1 or 0
Technology	Manufacturing ability	Qualitative	Scale point
	Quality variance	Quantitative	Percentage
	Fulfil rate	Quantitative	Percentage
	Lead time	Quantitative	Day
Cost	Production cost	Quantitative	$US
	Quality loss cost	Quantitative	$US
	Management cost	Quantitative	$US
	Customer loss cost	Quantitative	$US

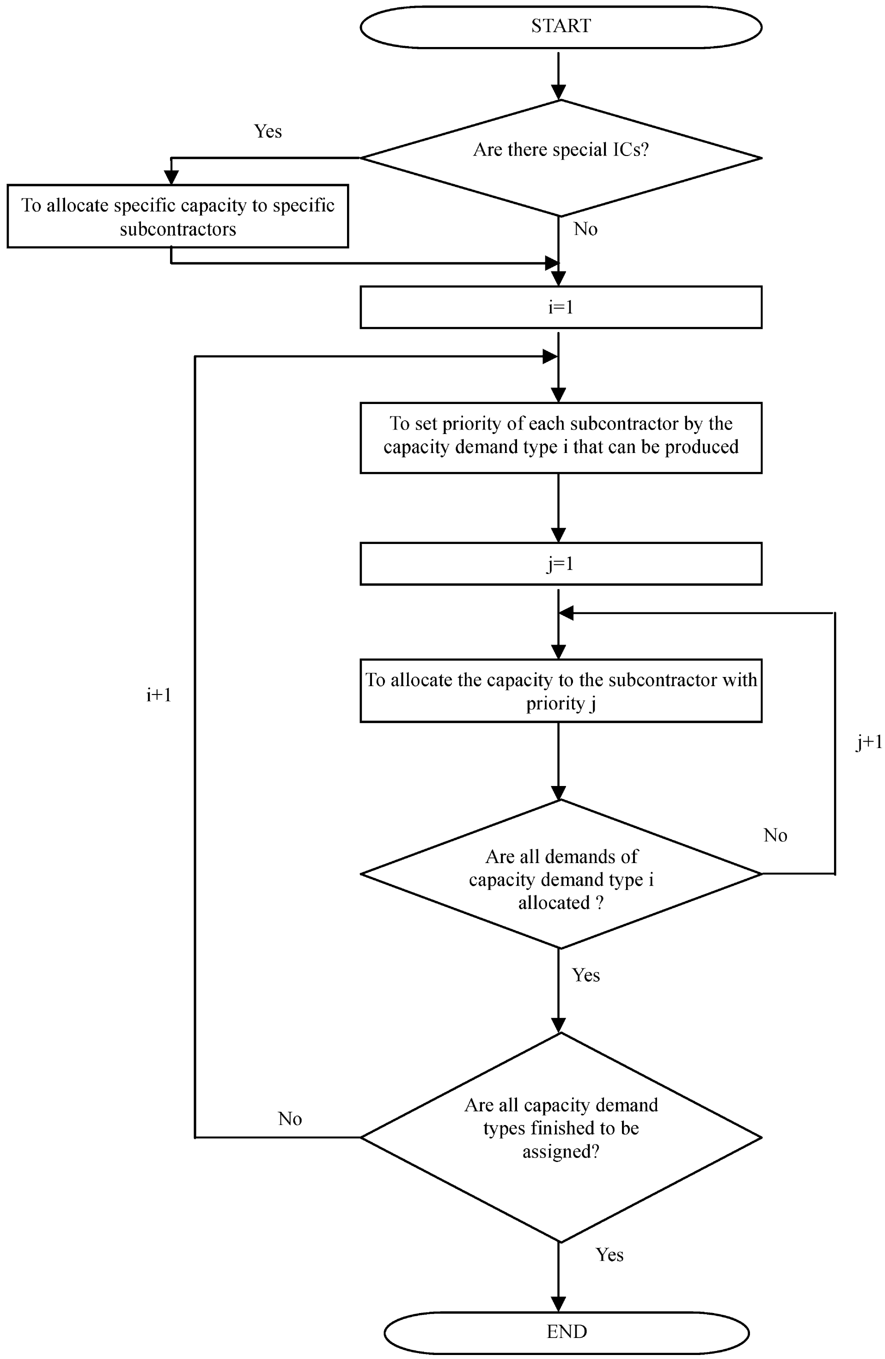


Fig. 7 Heuristic booking capacity planning

utility value, and the criterion with the largest weight at level 1 will receive the highest priority. If there is still no difference, then they will be compared by the next largest criterion at level 1. If they are still the same, and all criteria at level 1 have been exhausted, we will randomise the priorities of those subcontractors.

Step 4: Set $j=1$. The capacity demand allocation begins from the subcontractor with the highest priority j.

Step 5: Allocate the capacity demand to the subcontractor with priority j until the subcontractor's capacity is completely occupied.

Step 6: Check if all the demands of capacity demand type i are completely assigned. If yes, go to the next step; otherwise, let j add 1 and return to Step 5.

Step 7: Check if demands of all capacity demand types are completely assigned. If yes, then stop; otherwise, let i add 1 and return to Step 3.

At each stage, we use the HBCP to allocate the capacity demand and define the total utility value of booking capacity planning. Allocation quantity multiplies the value of the UI for each subcontractor. An IC design house measures the booking capacity plan by the total utility value and makes an adjustment. In the next section, we show the performance of the HBCP through an example.

4 Example

In order to demonstrate the performance of the proposed method, we took an example of an IC design house X that focuses on memory IC in the the Science-Based Industrial Park, Hsinchu, Taiwan, R.O.C. We chose ten product types from the company's main product line and got inventories and future demands, six month samples for each product, as shown in Table 8. Every two product types combine to make a product group. The bin split of product groups is the same as that which Leachman [10] presented. Other information about each product group and information of each subcontractor are provided in Tables 9, 10, 11, 12, 13, 14 and 15.

To get detailed demand plan, we split a month into four weeks with one week intervals.

Using the proposed method, we can get the net demand plan and net capacity demand plan in Tables 16, 17, 18 and 19. Before going to the HBCP process, we asked the key person in the IC design house X, who was responsible for the outsourcing capacity planning for the past 5 years, to execute the AHP process and obtain the weights of all factors. The weight of each factor is presented in Tables 20 and 21. The consistency ratio of each pairwise comparison matrix is shown in Table 22.

According to the subcontractor information that the IC design house X provided, we use the proportional scores method to find out the utility value of each factor and the value of the UI for each subcontractor (Table 23). It is assumed in this research that there are 5 wafer fabs, 5 assembly houses and 5 final test companies to be eligible for outsourcing. The next step is to trigger HBCP procedure to allocate the capacity demand. The booking capacity plan is presented in Figs. 8, 9, 10, 11 and 12.

In order to know the difference between our proposed method and the method that enterprises use in practice, we surveyed three IC design houses to understand their capacity allocation methods and to simulate a general method. However, the method of handling the capacity allocation problem varied for each company according to its own characteristics. The IC design house X divides subcontractors into two groups: primary and secondary. It allocates the capacity to the subcontractors of the primary group based on the relationship with IC design house X. If there are residual capacities that are not assigned yet, it allocates the capacity to the subcontractors in the secondary group by yield. If there are subcontractors with the same yield, the capacity is assigned with the consideration of the relationship.

The other two companies that master in memory IC in the Science-Based Industrial Park, Hsinchu, Taiwan, R.O.C. are also interviewed. In company Z, the allocation of capacity is decided by yield and due date. If there are not urgent demands, the first consideration is yield. Otherwise, the due date will be the secondary consideration. Company Y uses accommodation, cost, due date, yield, relationship and quantity to distribute the capacity demand.

Table 8 The inventories and future demands of each product type

Product type	Inventory	January	February	March	April	May	June
A	1200	2800	3150	1800	900	750	800
B	900	1200	350	200	600	750	200
C	560	1200	900	1050	800	500	250
D	370	800	600	450	200	500	250
E	400	800	600	500	500	400	400
F	100	200	400	500	500	100	100
G	310	280	560	700	750	1200	1800
H	90	120	240	300	750	800	200
I	150	160	140	180	800	700	900
J	25	40	60	120	200	300	100

Table 9 The WIP, the bin split and the cost of each product group

Product group	WIP of wafer fab	WIP of probe	WIP of assembly	WIP of final test	Production cost of final test ($US)	Bin	Bin split	Holding cost ($US/Die)
Group 1	100	300	400	250	100	Bin 1	0.9	0.4
						Bin 2	0.1	0.5
Group 2	100	50	100	50	100	Bin 3	0.8	0.8
						Bin 4	0.2	0.7
Group 3	80	100	150	50	300	Bin 5	0.6	0.6
						Bin 6	0.4	0.5
Group 4	20	20	10	10	200	Bin 7	0.5	0.9
						Bin 8	0.5	0.7
Group 5	10	10	5	5	300	Bin 9	0.5	0.1
						Bin 10	0.5	0.9

Table 10 The capacity requirement and specific subcontractor for each product group

Product group	Wafer fab	Specific subcontractor	Assembly	Specific subcontractor	Final test	Specific subcontractor
Group 1	0.18 μ	X	BGA	x	FT1, FT2, FT3	x
Group 2	0.25 μ	Fab2	TSOP	Assembly2	x	FT2
Group 3	0.25 μ	X	SOJ	x	x	x
Group 4	0.18 μ	X	TSOP	x	FT4, FT5	x
Group 5	0.18 μ	Fab5	BGA	Assembly5	x	FT5

Table 11 The data for the wafer fab

Vendor	Relation-ship[a]	Accommo-dation[b]	Supply capacity[c]	Specific factory[d]	Manufacturing ability[e]	Quality variance[f]	Fulfil rate[g]	Lead time[h]	Production cost[i]	Quality loss cost[j]	Management cost[k]
Fab 1	4	9	5400	0	8	0.053	0.98	40	3	0.08	160
Fab 2	3	5	6600	1	7	0.063	0.99	46	2.8	0.12	196
Fab 3	9	7	7200	0	7	0.065	0.95	49	3.2	0.1	154
Fab 4	6	2	5700	0	3	0.067	0.97	47	2.7	0.05	161
Fab 5	8	6	5200	1	5	0.055	0.98	37	2.3	0.09	159

[a] The higer score means the subcontractor has a better relationship with the IC design house
[b] The higer score defines the subcontractor has a better adaptability for IC design house
[c] The value shows the maximum capacity that the subcontractor can provide for the IC design house
[d] The value indicates the subcontractor has the capability to produce a specific IC. "1" presented there is this kind of IC. "0" indicated there is not
[e] The higher score denotes the subcontractor has a more advanced manufacturing ability
[f] The value means the variance degree of yield about the subcontractor
[g] T he value is the ratio of on-time-delivery that a subcontractor can provide
[h] The value defines the cycle time of the subcontractor
[i] The value is the cost that the subcontractor produces a thousand dies
[j] The value is the cost that the subcontractor handles a thousand failed dies
[k] The value is the cost that the subcontractor needs to manage the products

Table 12 The data for the BGA of the assembly

Vendor	Relation-ship	Accommo-dation	Supply capacity	Specific factory	Manufacturing ability	Quality variance	Fulfil rate	Lead time	Production Cost	Quality loss cost	Management cost	Customer loss cost[a]
Assembly 1	5	3	1500	0	8	0.059	0.98	6	0.2	0.012	151	7320
Assembly 2	9	7	1000	1	4	0.065	0.99	4	0.5	0.009	183	4880
Assembly 3	7	6	980	0	7	0.053	0.96	5	0.6	0.011	196	7320
Assembly 4	8	8	1200	0	6	0.054	0.99	5	0.8	0.01	169	2440
Assembly 5	3	5	2300	1	5	0.067	0.95	6	0.5	0.008	171	4880

Table 13 Data for the TSOP of the assembly

Vendor	Relation-ship	Accommo-dation	Supply capacity	Specific factory	Manu-facturing ability	Quality variance	Fulfil rate	Lead time	Production cost	Quality loss cost	Management cost	Customer loss cost
Assembly 1	5	3	820	0	8	0.059	0.98	6	0.1	0.012	151	7320
Assembly 2	9	7	1700	1	4	0.065	0.99	4	0.3	0.009	183	4880
Assembly 3	7	6	840	0	7	0.053	0.96	5	0.1	0.011	196	7320
Assembly 4	8	8	1400	0	6	0.054	0.99	5	0.1	0.01	169	2440
Assembly 5	3	5	950	1	5	0.067	0.95	6	0.1	0.008	171	4880

Table 14 The data for the SOJ of the assembly

Vendor	Relationship	Accommodation	Supply capacity	Specific factory	Manufacturing ability	Quality variance	Fulfil rate	Lead time	Production cost	Quality loss cost	Management cost	Customer loss cost
Assembly 1	5	3	100	0	8	0.059	0.98	6	0.4	0.012	151	7320
Assembly 2	9	7	500	1	4	0.065	0.99	4	0.3	0.009	183	4880
Assembly 3	7	6	280	0	7	0.053	0.96	5	0.2	0.011	196	7320
Assembly 4	8	8	140	0	6	0.054	0.99	5	0.2	0.01	169	2440
Assembly 5	3	5	300	1	5	0.067	0.95	6	0.1	0.008	171	4880

Table 15 The data for the final test

Vendor	Relationship	Accommodation	Supply capacity	Specific factory	Manufacturing ability	Quality variance	Fulfil rate	Lead time	Production cost	Quality loss cost	Management cost	Customer loss cost
FT 1	8	9	2400	0	6	0.061	0.98	8	0.1	0.005	147	5856
FT 2	5	3	4600	1	5	0.071	0.96	7	0.1	0.014	160	5856
FT 3	6	9	2500	0	7	0.057	0.98	6	0.3	0.009	176	1952
FT 4	9	4	3500	0	4	0.054	0.99	5	0.3	0.01	168	3904
FT 5	2	5	2300	1	2	0.064	0.97	8	0.2	0.012	195	3904

Table 16 The net demand plan of the final test (Unit: Thousand Dies)

Period group	1	2	3	4	5	6
1	1894.25	3065.8	1875	1885	1260	500
2	1257.25	1431.6	1375	1250	740	240
3	642.98	904.15	937.49	1062.5	458.34	333.34
4	182.56	1174.12	1430	2340	3000	1800
5	71.23	291.88	670	1900	1600	900

Table 17 The net capacity plan of the wafer fab (Unit: Thousand Dies)

Period		1	2	3	4	5	6
Month	0.18 μ	4350.97	5463.51	5396.79	8114.5	7895.54	2060.83
	0.25 μ	3252.54	2954.81	2951.69	2656.53	1510.21	369.24

Table 18 The net capacity plan of the assembly (Unit: Thousand Dies)

Period		1	2	3	4	5	6
Month	BGA	2136.39	3649.65	2766.3	4114.13	3108.7	1521.74
	TSOP	1565.01	2832.3	3048.91	3902.17	4065.22	2217.39
	SOJ	698.89	982.77	1019.01	1154.89	498.2	362.33

According to the abovementioned description, there are three main factors to be considered when an IC design house allocates its capacity demand. Relationship is the first important factor that affects the capacity allocation because an IC design house usually has one or two partners at each outsourced stage. Yield is also an important factor for an IC design house.

Table 19 The net capacity plan of the final test (Unit: Thousand Dies)

Period Group	1	2	3	4	5	6
1	1014.25	3445.8	2000	1880	1390	750
2	882.25	1431.6	1500	1250	870	360
3	392.98	945.82	833.32	1312.5	354.17	500.01
4	22.56	984.12	1400	2120	2700	2700
5	11.23	261.88	360	1950	1500	1350

Table 20 The weights of the criteria at level 1

	Wafer fab	Assembly	Final test
Management	0.08	0.79	0.16
Technology	0.43	0.08	0.59
Cost	0.49	0.13	0.25

Table 21 The weights of factors at level 2

	Wafer fab	Assembly	Final test
Relationship	0.10	0.08	0.19
Accommodation	0.06	0.06	0.17
Supply capacity	0.27	0.21	0.51
Specific factory	0.57	0.65	0.13
Manufacturing ability	0.13	0.21	0.27
Quality variance	0.27	0.19	0.16
Fulfil rate	0.06	0.06	0.33
Lead time	0.54	0.54	0.24
Production	0.64	0.29	0.29
Quality loss	0.28	0.44	0.44
Management	0.08	0.22	0.22
Customer loss	X	0.05	0.05

Table 22 The consistency ratio of each pairwise comparison matrix

	Wafer fab	Assembly	Final test
Matrix of level 1	0.01	0.05	0.05
Management matrix of level 2	0.08	0.09	0.06
Technology matrix of level 2	0.08	0.09	0.08
Cost matrix of level 2	0.06	0.04	0.04

Table 23 The U.I. and the priority of each subcontractor

Stage	Subcontractor	U.I.	Priority	Capacity status
Wafer fab	Fab 1	0.56	2	0.18 μ
Wafer fab	Fab 2	0.36	4	0.25 μ
Wafer fab	Fab 3	0.17	5	0.25 μ
Wafer fab	Fab 4	0.41	3	0.18 μ
Wafer fab	Fab 5	0.84	1	0.18 μ
Assembly	Assy 1	0.18	4	BGA
Assembly	Assy 2	0.74	2	BGA
Assembly	Assy 3	0.15	5	BGA
Assembly	Assy 4	0.23	3	BGA
Assembly	Assy 5	0.80	1	BGA
Assembly	Assy 1	0.12	5	TSOP
Assembly	Assy 2	0.89	1	TSOP
Assembly	Assy 3	0.18	4	TSOP
Assembly	Assy 4	0.35	3	TSOP
Assembly	Assy 5	0.68	2	TSOP
Assembly	Assy 1	0.08	5	SOJ
Assembly	Assy 2	0.90	1	SOJ
Assembly	Assy 3	0.24	3	SOJ
Assembly	Assy 4	0.24	4	SOJ
Assembly	Assy 5	0.73	2	SOJ
Final test	FT 1	0.54	3	Can't test product group 4
Final test	FT 2	0.37	4	Can't test product group 4
Final test	FT 3	0.61	2	Can't test product group 4
Final test	FT 4	0.66	1	Can't test product group 1
Final test	FT 5	0.20	5	Can't test product group 1

Yield represents the quality and stability of each subcontractor and affects quantity of finished goods. Finally, the due date is another key factor. It makes an impact on market share and profit.

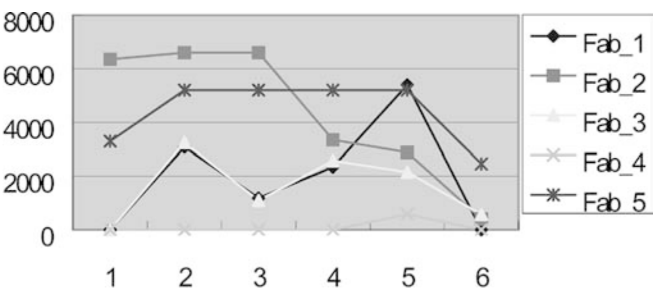


Fig. 8 The capacity allocation of a wafer fab for HBCP

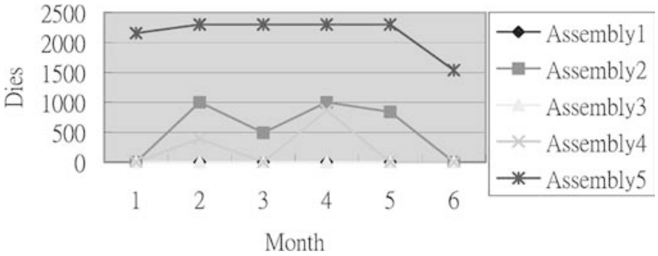


Fig. 9 The BGA capacity allocation of the assembly for HBCP

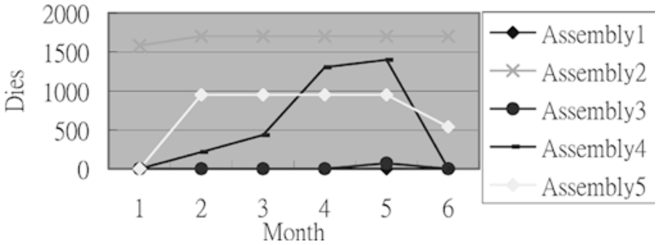


Fig. 10 The TSOP capacity allocation of the assembly for HBCP

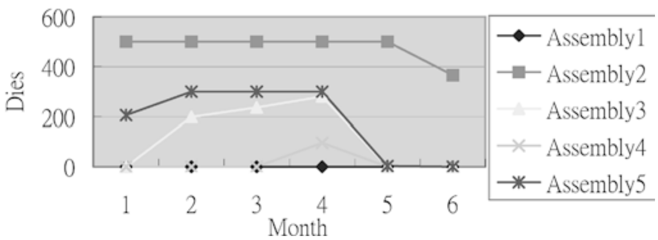


Fig. 11 The SOJ capacity allocation of the assembly for HBCP

This study applies the three factors to simulate a practical logic for an enterprise, which is called the practice approach, below. We selected two subcontractors with the highest relationship scales to be the primary group at each stage and allocated the capacity according to the relationship priority. The rest subcontractors at each stage belong to the secondary group and set the priority by yield. If there were subcontractors with the same yield, the priority was determined by the due date. We used the practice approach to compare the total utility value with HBCP. The capacity allocation plan of the practice approach is shown in Figs. 13, 14,

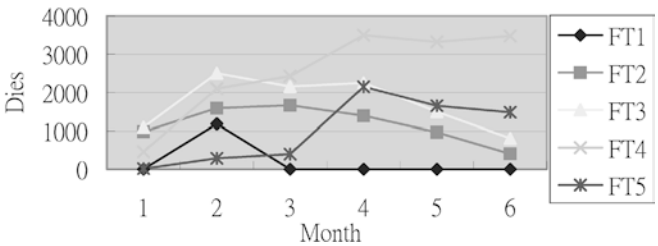


Fig. 12 The capacity allocation of the final test for HBCP

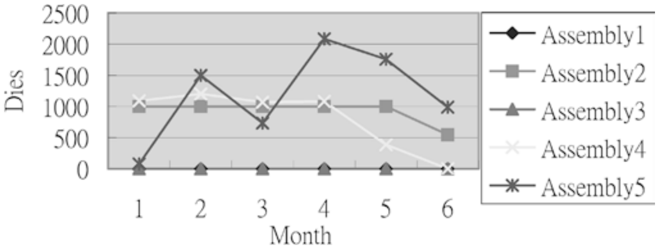


Fig. 14 The BGA capacity allocation of the assembly for the practice approach

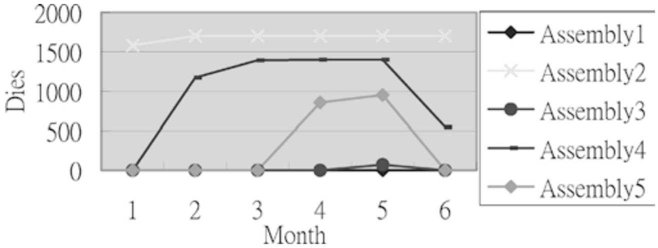


Fig. 15 The TSOP capacity allocation of the assembly for the practice approach

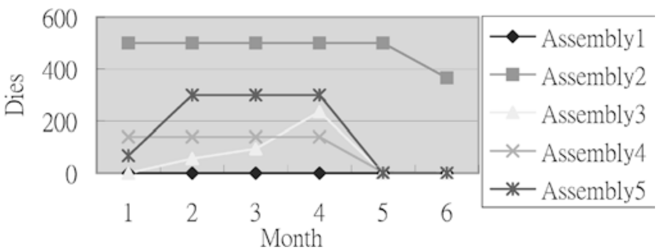


Fig. 16 The SOJ capacity allocation of the assembly for the practice approach

15, 16 and 17. Table 24 indicates the difference of the total utility value between the practice approach and HBCP.

Since Lin et al. [9] compared the LP model with the traditional MRP in terms of the net demand plan, this study only presents a comparison of BCP based on the same net demand plan. The detailed discussion of each stage is as follows.

In the wafer fab, the utility values of management and technology for HBCP are higher than those of the practice approach, but the utility value of cost for HBCP is lower than that of the practice approach. Because yield is the secondary consideration of the practice approach, the cost value would be a little better. We also find the priority of criteria at level 1 based on the utility value of each criterion in Table 25. For the practice approach, the priority is Cost > Technology > Management. For the HBCP, its priority is Technology > Cost > Management. The total utility value of the HBCP is higher than that of the practice approach.

In the assembly, the HBCP has a better performance in management and cost, but the utility value of the technology for HBCP is lower than that of the practice approach. The total utility value of HBCP is higher than that of the practice approach. According to Table 25, the priority of criteria at level 1 for the practice approach is Management > Cost > Technology, and that for the HBCP is also Management > Cost > Technology. Although the priorities are the same, the ratio of each criterion is different. The management ratio of the HBCP (85.15%) is higher than that of the practice approach (82.97%). In the cost ratio, the HBCP (10.93%) and the practice approach (11.22%) are close. However, the technology ratio of HBCP (3.92%) is smaller than that of the practice approach (5.80%). This is why the practice approach performs better in technology criterion.

In the final test, the HBCP is better than the practice approach in the technology value, but the utility value of cost for HBCP is smaller than that of the practice approach. The management value of the HBCP is close to that of the practice approach. In sum, the total utility value of the HBCP is slightly higher than that of the practice approach. Because the yield of the practice approach has a higher priority than that of the HBCP, the practice approach generates a better performance in cost value. The priority of criteria at level 1 for the HBCP is Technology > Cost > Management shown in Table 25. The practice approach has the same priority sequence as the HBCP. However, the technology ratio of the HBCP (68.51%) is higher than that of the practice approach (61.04%). The cost ratio of the HBCP (18.15%) is lower than that of the practice approach

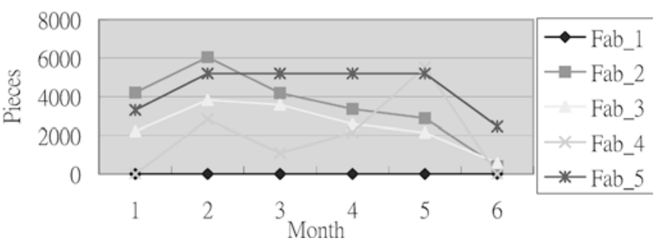


Fig. 13 The capacity allocation of the wafer fab for the practice approach

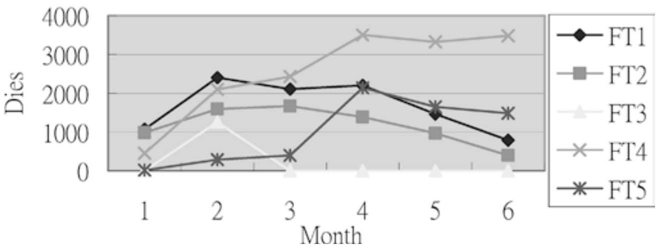


Fig. 17 The capacity allocation of the final test for the practice approach

Table 24 The comparisons between the practice approach and the HBCP

Stage	Method	Management	Technology	Cost	Total
Wafer fab	The practice approach	3383.07	14829.11	18883.89	37096.07
	HBCP	3527.24	19154.43	17584.62	40266.29
Assembly	The practice approach	22100.96	1545.62	2989.90	26636.48
	HBCP	25250.77	1163.79	3240.15	29654.71
Final test	The practice approach	2803.87	12234.16	5003.22	20041.24
	HBCP	2768.24	14209.92	3763.85	20742.01

Table 25 The ratio of each criterion for the practice approach and HBCP

Stage	Method	Management	Technology	Cost	Total
Wafer fab	The practice approach	9.12%	39.97%	50.91%	100.00%
	HBCP	8.76%	47.57%	43.67%	100.00%
Assembly	The practice approach	82.97%	5.80%	11.22%	100.00%
	HBCP	85.15%	3.92%	10.93%	100.00%
Final test	The practice approach	13.99%	61.04%	24.96%	100.00%
	HBCP	13.35%	68.51%	18.15%	100.00%

(24.96%). The management ratio of the HBCP (13.99%) and the practice approach (13.35%) are close.

From the abovementioned discussion, the logic of the HBCP is similar to the one of the practice approach, but the performance of the HBCP is better. We found that the HBCP mimics the human decision-making process in this sample problem and has a good effect on BCP. Meanwhile, the practice approach simplifies human judgment and results in a poorer performance.

The complete hierarchical framework represents the decision logic of the planner. It is easy to modify weights of all criteria to correspond with management thinking. We also can employ our proposed method to show the logic of the practice approach. The HBCP provides enterprises a good method to deal with capacity allocation problem. It is convenient in its application.

5 Conclusions

Special production characteristics of outsourcing capacity planning make the traditional production plan inapplicable in an IC design house. The framework presented in this research serves as a useful tool to formulate outsourcing capacity models and to solve problems in net IC product demand planning, net capacity demand planning, and BCP. We used the LP model to estimate the net IC demand and then transformed product demands into capacity demands so that an IC design house could clearly identify how much capacity was needed and should be allocated at each stage. The AHP and proportional scores methods were employed to define the UI of subcontractors at each stage. We proposed the HBCP to handle capacity allocation problem. The results of the HBCP were much better than those of the practice approach. The HBCP approximates the decision process of field managers to provide a BCP with a better performance.

However, when the forecast demand is updated each month, the difference between the old foregoing demand and newly updated demand will occur. Adjustment needs to be made for the OCP, taking the difference into account. Most planners or subcontractors hope that the plan will not change, or that only few parts of the plan can be changed. Therefore, dealing with the difference is an important task for a future study.

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