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Full Length Research Paper

Applying the fuzzy analytic network process to the selection of an advanced integrated circuit (IC) packaging process development project

Yung-Hsiang Hung*, Mei-Ling Huang and Kun-Liang Fanchiang

Department of Industrial Engineering and Management, National Chin-Yi University of Technology, 35, Lane215,
Section 1, Chung-Shan Road, TaiPing, TaiChung, 411, Taiwan, R.O.C.

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In the modern business environment, process technology evaluation and selection (PTES) is a crucial component of innovation in new product development (NPD). The most difficult task for project managers in PTES is to make the optimal technology choice for a Research and Development (R&D) project, and there are many attendant uncertainties and risks in process technology R&D projects for NPD. Recently, Integrated Circuit (IC) Packaging has become an equal part of the cost-performance equation in the silicon world, and packaging foundries have responded quicker than many other semiconductor companies to the rapidly changing requirements of chip-scale packaging. This facilitates the transfer of new technology from the assemblers to the chip suppliers. This study applies the fuzzy analytic network process (FANP) model to evaluate the strategic impact of new IC manufacturing technologies in firms within Taiwan's IC packaging industry. Our study will determine the key decision-making factors affecting R&D project selection using FANP, and additionally we develop an optimal manufacturing process. As a case study, the ongoing "Controller IC packaging R&D project A" was chosen to minimize warpage of controller IC.

Key words: Integrated Circuit (IC) packaging technology, controller integrated circuit (IC), new product development, Research and Development (R&D) project selection, fuzzy analytic network process (FANP).

INTRODUCTION

In today's fiercely competitive global economy, new product development (NPD) is widely considered as an essential activity contributing towards the success, survival and renewal of organizations (Brown and Eisenhardt, 1995). A key NPD activity that firms use to reduce the risks and uncertainties associated with new products is the careful selection of new potentially successful product ideas and technological process innovations. As process technology evaluation and selection (PTES) is vital to technological process innovation in NPD, technology is seen as a driving force of innovation. In particular, PTES involves determining the process technical requirements of a new product and assessing how well they match the firm's technical capabilities. This can assist firms in addressing technical and manufacturing problems early in the NPD process, and permits the rapid introduction of new products onto the market. However, in the PTES production process, the most difficult task for project managers is making the correct technology Research and Development (R&D) project choice, as a poor R&D selection commonly leads to either failure of that product in the market place or an extended product development time. Understanding customer needs and making the correct R&D project choice will lead to the development of successful products and a reduced development time.

R&D project selection is an indispensable resource for progressive hi-tech companies in the semiconductor industries, especially those that depend on innovation such

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*Corresponding author. E-mail: hung.yunghsiang@gmail.com. Tel: 886 4 23924505 ext. 7628. Fax: 886 4 23934620.

as Integrated Circuit (IC) Packaging companies.

The key to continued competitiveness lies in their ability to develop and implement new product and process technologies. Project selection is the process of evaluating individual R&D projects, that is, to choose the right project based analysis, with the aim of achieving the company's objectives. It involves a thorough analysis, including the important time-to-market aspect to determine the optimum project from the alternatives. Unfortunately, there are attendant uncertainties and risks associated with R&D projects for NPD. Uncertainty arises from multiple sources, including technical, management and commercial issues, and may be both internal and external to the project (Feyzioğlu and Büyüközkan, 2006). However, R&D project managers are faced with complex decision-making environments and project problems. Recent literature on R&D project evaluation and selection features of many decision models uses a wide range of mathematically-based approaches. Criticisms of these techniques include their inability to consider strategic factors and their mathematical complexity (Albala, 1975; Fahrni and Spätig, 1990; Lockett et al., 1986; Meade and Presley, 2002). A multi-attribute decision-making approach is commonly used in the assessment and selection of alternative projects. The analytic hierarchy process (AHP) is perhaps the most widely used decision-making approach (Sevkli et al., 2008). It is a decision-aiding method developed by Saaty (2008), and its validity is based on the many hundreds (and now thousands) of actual applications in which AHP results were accepted and used by cognizant decision-makers (DMs). AHP is mainly used to solve the decision-making problems of multi-factor assessment with uncertainties (Chan et al., 2004). However, in the problem-solving process, the hierarchical analysis conducts an assessment by systematizing complex problems while assuming the factors of each hierarchy are independent. Many decision-making problems cannot be structured hierarchically; otherwise, strong interactions and dependencies would exist between inter-level and intra-level elements.

To solve the aforementioned problems, Saaty (2001) proposed the analytic network process (ANP) to take into consideration the inter-hierarchy relations, that is, the relations and interactions of factors of both the high-hierarchy and low-hierarchy. The hierarchical structure is linear in the hierarchical analysis, and has a non-linear network structure in network hierarchal analysis. The network hierarchical analysis features interdependence and feedback characteristics, and a super-matrix is applied to the weight calculation. This process has a higher level strategic hierarchy that controls all the benefit, cost, risk and opportunity sub networks required by the specific R&D project management problem. Despite their popularity, AHP and ANP have been frequently criticized for their inability to adequately handle the inherent uncertainty and imprecision associated with the mapping of a DM's perception to group members.

Because conflicts always occur in group decision-making, and members may not always be in agreement initially, ANP has an inherent weakness in capturing the vagueness, uncertainty and imprecision of judgments given by different members of an expert group. This may be caused by their varying levels of experience, a lack of experimental data and other unknown factors. In real world decision-making problems, decision-making with fuzzy set theory enabled one to reach the aim in a quicker, easier and more sensitive way (Nataraja et al., 2006).

Due to the trend of developing thinner consumer electronics products, the R&D of thinner IC packaging technology has become a major focus of technological innovation for IC packaging factories around the world. IC manufacturing technologies have continued to evolve from their original prototypes. Thinner IC packaging makes the quality problem of warpage in the IC packaging process a serious issue. The semiconductor foundry industry, whose core business is IC manufacturing, has been greatly influenced and shaped by the flow of these newly developed technologies. As the R&D of IC packaging manufacturing technology requires considerable time and cost to be expended, the product R&D and marketing period can be shortened if the opinions of experts in marketing, R&D and manufacturing can be effectively and quickly integrated. The problems discussed in the present study are common and widespread in the management of R&D in today's major packaging factories. In fact, the R&D of thinner IC manufacturing process technologies involves the expertise of many different areas. The fuzzy ANP (FANP) project selection method applied in the present study can systematically and rapidly integrate the expertise of various areas, saving a significant amount of time and enabling firms to rapidly carry out the R&D of the product manufacturing process technologies. This method allows group members to express fuzzy preferences for alternatives and individual judgments for solution selection criteria. It has been proven to overcome the limitations of the compensatory approach and the inability of ANP in handling proper linguistic variables.

LITERATURE REVIEW

In today's rapidly changing business environment, innovative R&D projects for new products are growing quickly in terms of employment and profitability. New IC product design problems can be divided into four groups: strategic design, innovative design, variant design and repeat order electronics engineering product development (Culverhouse, 1993). In general, innovative design changes the product by 20 to 50% and requires the considerable input of either product or manufacturing technologies. It consists of four basic components: concept selection, component selection, material selection and process technology selection. In particular, process technology selection signifies the determination of the best pathway from which a specified product or service can be provided, through selection from a number of competing alternative processes. Accordingly, the first step in any such R&D activity is to understand the critical success factors of R&D competence which make the difference between success and failure at NPD.

Cooper and Kleinschmidt (1995) pointed out three factors critical to the success of a project: 1) the nature of the product, as a uniquely high quality product will yield better than expected economic returns for the customers; 2) the nature of the market, measured by market demand intensity, market growth rate and market scale; and 3) technical implementation and synergy of new products and existing products. In recent years, many studies have investigated a wide variety of factors affecting a new product's viability, both technologically as well as commercially. Meade and Presley (2002) reviewed literature and classified current R&D project selection methods into three major themes, that is, the need to relate selection criteria to corporate strategies, the need to consider the qualitative benefits and risks of candidate projects, and the need to reconcile and integrate the needs and desires of different stakeholders. In spite of this, different views exist regarding the relevance of success factors. On the whole, there is a consensus of opinions, as researchers seem to agree that the market, technology, environment and organization classes of variables are important (Lilien and Yoon, 1989).

R&D is seen as a driving force of innovation. However, given the magnitude of variables and stakeholders involved, R&D managers face a difficult challenge determining the measures that are useful for measuring product development success. R&D project selection involves uncertainty and a high level of risk (Mohamed and McCowan, 2001). Therefore, the decision-making aspect of R&D project selection requires the cooperation of business organizations at different levels. R&D decisions which are necessary at early stages of development contain a considerable amount of elements which cause uncertainty, potentially confusing the DM‘s efforts to achieve the target performance. For the above reasons, the project selection process and result are a key step in the success of R&D for IC packaging technology development (Martino, 2004).

Considerable efforts have been made in the past four decades to assist organizations in making better decisions in R&D project evaluation and selection (Martino, 2004; Henriksen and Traynor, 1999; Ringuest et al., 2004). Some models are strictly empirical and are based on statistical analysis of the correlation between project characteristics and project success (Cooper and Kleinschmidt, 1995). AHP is the most widely used decision-making approach in the world today (Sevkli et al., 2008). AHP combines qualitative analysis with quantitative analysis, and uses a fundamental scale of absolute numbers that has been proven in practice and validated by physical and decision problem experiments. A number of scholars have studied AHP to improve the quality of PTES decision-making (Gerdsri, 2005; Bhattacharya et al., 2004; Ong et al., 2003; Chen et al., 2005) applied AHP to evaluate the strategic impact of new IC manufacturing technologies in the semiconductor foundry industry in Taiwan (Chen et al., 2005). The results show the relative importance of competitive goals in the semiconductor foundry industry. Each competitive goal is aligned to technology strategies as well as to emerging technologies in the prioritized order. However, in a multi-project environment, the success of an R&D project is not solely dependent on the project management team, as no functional managers can be omitted from the decision-making process (Mohanty et al., 2005). Thus, to analyze project alternatives, a feedback loop is necessary for each of these functional organizations at each level of maturity of the project. As such, ANP has been chosen as a decision-making tool to aid such analysis. The most important advantage of ANP over AHP is that ANP is a holistic approach in which all criteria and alternatives involved are connected in a network system that accepts various dependencies (Saaty, 2008). ANP enables users to take into consideration the degree of interdependences between the judgments of DMs and the processes' technical requirements by means of AHP. The key to success in an R&D project is to establish consistent group judgment (Schmidt and Freeland, 1992; Åstebro, 2004). Nevertheless, conflict always occurs in group decision-making since members in a group generally do not reach a unanimous decision. Previous studies have already considered the fuzzy set theory for prioritizing R&D project decisions (Saaty, 2008). For example, some researchers used the concept of fuzzy theory combined with AHP to address the uncertainty of human thinking (Kahraman et al., 2006; Wu et al., 2004; Wang et al., 2005; Mikhailov and Singh, 2003). Meade and Presley (2002) applied the ANP proposed by Saaty (2001) to the selection of the R&D project while developing a complete decision-making support system. The R&D project selection related literature is summarized in Table 1.

FUZZY ANALYTIC NETWORK PROCESS (FANP)

Review of the analytic network process (ANP)

The ANP is the most comprehensive framework for the analysis of societal, governmental, and corporate decisions available to the modern DM. The key concept of the ANP is that influence does not necessarily have to flow only downwards, as is the case with the hierarchy in the AHP. Influence can flow between any factors in the

Table 1. Summary of the R&D project selection related literature.

Author	Method
Chan et al., (2004) and Mohamed and McCowan (2001).	Using AHP to solve the decision-making problems of multi-factor assessment with uncertainties.
Saaty (2001)	Proposed the ANP to take into consideration the inter-hierarchy relations, to solve the aforementioned problems.
Cooper and Kleinschmidt (1995)	Pointed out three factors critical to the success of a project: 1) the nature of the product, 2) the nature of the market, and 3) technical implementation and synergy of new products and existing products.
Martino (2004), Henriksen and Traynor (1999) and Ringuest et al. (2004)	To assist organizations in making better decisions in R&D project evaluation and selection.
Chen et al. (2005)	Applied AHP to evaluate the strategic impact of new IC manufacturing technologies in the semiconductor foundry industry in Taiwan.
Schmidt and Freeland (1992) and Åstebro (2004)	The key to success in an R&D project is to establish consistent group judgment.
Kahraman et al. (2006), Wu et al. (2004), Wang et al. (2005) and Mikhailov and Singh (2003)	Using the concept of fuzzy theory combined with AHP to address the uncertainty of human thinking
Meade and Presley (2002)	Applied the ANP proposed by Saaty (2001) to the selection of the R&D project while developing a complete decision-making support system.

network, causing non-linear results for the priorities of scenario choices. In general, ANP models have two parts. The first is a control hierarchy or network of objectives and criteria that control the interactions in the system under study. The second part of the ANP model is the many sub-networks of influences among the elements and criteria of the problem, with one for each control criterion. An outline of the steps of the ANP is as follows:

Step 1: Determine the control hierarchies, including their criteria for comparing the components of the system and their sub-criteria for comparing the elements of the system.

Step 2: Computed derived weights are used later to weigh the elements of the corresponding column criteria of the super-matrix corresponding to the control criterion. Firstly, a pair-wise comparison matrix is set up. Secondly, the super-matrix limit (eigenvector) is computed. Thirdly, consistency analysis is performed. Lastly, the limiting priorities using each super matrix are computed.

Step 3: Synthesize the limiting priorities by weighing each limiting super-matrix with the weight of its control criterion and adding the resulting super-matrices.

The ANP allows one to include all factors and criteria, both tangible and intangible, which relate to making the best decisions. It allows both interaction and feedback within clusters of elements (inner dependence) and between clusters (outer dependence). Such feedback best captures the complex effects of interplay in human society, especially when risk and uncertainty are involved (Sevkli et al., 2008; Saaty, 2008).

A so-called super-matrix, describing the interaction between the components of the system, is constructed from the priority vectors (eigenvectors). It can be used to assess the results of feedback. Each of the columns is an eigenvector that represents the impact of all the elements in the i^{th} component on each of the elements in the j^{th} component. Interaction in the super-matrix is measured according to several possible criteria, in which priorities and relations are represented in a control hierarchy as shown in Figure 1. Sub-matrix X represents a pair-wise comparison matrix of cluster A under hierarchy C, sub-matrix D represents a pair-wise comparison matrix of cluster C under hierarchy A and sub-matrix E represents a pair-wise comparison matrix of cluster A with a dependency relationship.

There is no pair-wise comparison matrix in hierarchy C, due to the absence of a dependency relationship. Hence, the super-matrix is shown as follows:

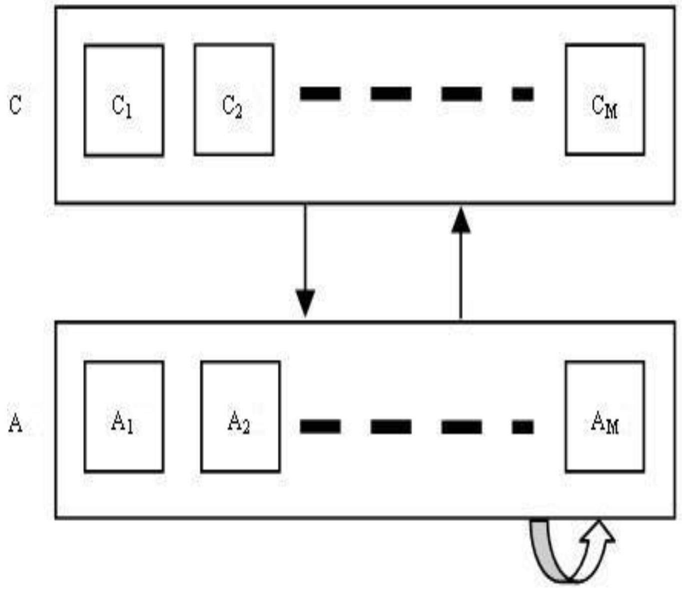

Figure 1. The structure of the ANP.

$$M' = \begin{array}{c} \\ \mathrm{A} \\ \mathrm{C} \end{array} \begin{array}{c} \begin{array}{cc} \mathrm{A} & \mathrm{C} \end{array} \\ \begin{bmatrix} \mathrm{E} & \mathrm{X} \\ \mathrm{D} & 0 \end{bmatrix} \end{array} \tag{1}$$

M' is an unweighted super-matrix. If the matrix does not conform to the column-stochastic rule (sum of column value =1), the weighted super-matrix *M* can be obtained through the weight conversion procedure until the sum of each column is 1. The weighted super-matrix is then limited, namely, *M* is multiplied by *M* to the power of *2K+1* to converge the dependency relationship. The relative weight of all elements is computed (Saaty, 2008). Finally, the desirability index (DI) in Equation 2 is used to judge an optimal solution.

$$DI_i = \sum_{j=1}^{r} S_{ij} = \sum_{j=1}^{r} R_j W_{ij} \tag{2}$$

DI_i, Desirability index of i^{th} feasible solution; S_{ij}, weight of i^{th} feasible solution under j^{th} element; R_j, relative weight of j^{th} element; W_{ij}, relative weight of i^{th} solution under j^{th} element.

A feasible solution with the highest DI is optimal solution A^*, as shown in Equation 3:

$$A^* = \left\{ A_i \mid DI_i = \max_{k=1,2,\ldots,n} imum\left(DI_k\right) \right\} \tag{3}$$

Fuzzy pair-wise comparison matrix

A set of ANP pair-wise comparison matrices was constructed for each of the lower levels with one matrix for each element in Equation 3, using the relative scale measurement as shown in Table 2. If each entry in *E* is denoted by e_{ij}, then $e_{ij} = 1/e_{ij}$ (the reciprocal property) holds, and so does $e_{jk} = e_{ik}/e_{ij}$ (the consistency property). By definition, $e_{ii} = e_{jj} = 1$ (when comparing two elements which are the same). Given the subjectivity, uncertainty, and fuzziness of experts' evaluation on an R&D project, the results evaluated from the ANP may differ from the actual situation. Some researchers represented uncertain judgments as fuzzy sets of fuzzy numbers e_{ij}. The fuzzy scale relating relative preferences, measuring the relative weights is given in Table 2.

Laarhoven and Pedrycz (1983) and Buckley et al. (2001) modified the AHP for a fuzzy hierarchical analysis using comparison matrices with triangular fuzzy numbers. They obtained fuzzy priorities $\tilde{a}_{ij}$, *i,j =1, 2, …, n* by applying a fuzzy version of the Logarithmic least squares method. If the pair-wise comparison matrix of the k^{th} expert amongst *N* experts is transformed into a fuzzy pair-wise comparison matrix $\tilde{A}^K\left(a_{ij}\right)$, the result is as shown in Equation 4.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12}\left(L,M,R\right) & \cdots & \tilde{a}_{1n}\left(L,M,R\right) \\ \dfrac{1}{\tilde{a}_{12}\left(L,M,R\right)} & 1 & \cdots & \tilde{a}_{2n}\left(L,M,R\right) \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{1}{\tilde{a}_{1n}\left(L,M,R\right)} & \dfrac{1}{\tilde{a}_{2n}\left(L,M,R\right)} & \cdots & 1 \end{bmatrix} \tag{4}$$

After the fuzzy pair-wise comparison matrices of all experts are established, the weights of all experts are collectively computed by the geometric average (shown in Equation 5) recommended by Buckley et al. (1999).

$$\tilde{W} = \left[\prod_{k=1}^{N} \tilde{A}^k \right]^{1/N} \tag{5}$$

There are a number of defuzzification methods in fuzzy set theory, of which the commonly used methods include center of gravity, area, height, midpoint of maximum and the weighted average method. In this paper, defuzzification is affected with center of gravity of Equation 6 proposed by Hsieh et al. (2004).

$$\mathrm{DF} = \left[\left(\mathrm{R-L}\right) + \left(\mathrm{M-L}\right)\right]/3 + \mathrm{L} \tag{6}$$

Table 2. Pair-wise comparison scales for AHP and triangular fuzzy scales.

Verbal judgments of preferences	AHP numerical scale	Triangular fuzzy scale
Extremely preferred	9	(8, 9, 9)
Very strongly preferred	7	(6, 7, 8)
Strongly preferred	5	(4, 5, 6)
Moderately preferred	3	(2, 3,4)
Equally preferred	1	(1, 1, 2)

CASE STUDY

Semiconductor manufacturing has many distinct segments, including design, marketing, masking, manufacturing, testing, and packaging. Packaging protects the IC and provides its interconnections, power, and cooling. As packaging sizes continue to decrease, the level of integration of semiconductor devices continues to increase in complexity as well as the number of components. Competitive IC manufacturing must accommodate this trend without increasing the cost of manufacture. In order to develop competitive IC packaging products with a high performance/cost ratio, design schemes should be optimized in terms of technical capacity, economic benefit, product performance, risk management, and so on (Balachandra and Friar, 1997). Most semiconductor IC packaging foundries have developed fine-pitch ball grid array (FPBGA) packages using laminate and polyimide interposers. Dozens of new packaging styles have been developed for specific applications, and much of this work has occurred at the assemblers. Therefore, IC packaging must also evolve to accommodate the changing trends in IC technology (such as BGA, Chip Scale Package, Multi Chip Modules and Flip-Chip etc) (Tummala, 2001). However, R&D personnel are technically trained perfectionists who believe that cost and time are relatively unimportant when it comes to improving a technology. Very few people in an organization truly understand the R&D environment and the problems faced by R&D managers. In fact, technology is the strategic problem of the IC packaging process requiring a model that evaluates several criteria in different dimensions. These dimensions are required for ranking them according to the likelihood of their being a goal, according to Cheng and Wu (2004), Huang et al. (2008) and Taiwan's IC packaging experts. This study employed four dimensions, that is, technological merit (TM), potential benefits (PB), availability of resources (AOR), and R&D risks (RDR), to evaluate the micro HDD controller IC's packaging project in a central Taiwan IC packaging company. The experts surveyed for the case study include a project manager, risk analysis and assessment engineer, material science engineer, structure engineer (model construction and simulation analysis), equipment engineer, manufacturing process engineer, debugging engineer and product engineer. The standard network and a description of the criteria are listed and shown in Figure 2.

The controller IC packaging process of the R&D network is constructed based on the dimensions in Figure 2. However, project selection in the IC packaging process involves many uncertainties, such as different expert opinions and project team members have varying attitudes to the project. Ambiguity and uncertainty inevitably produce risks which may hamper project objectiveness when an assessment is carried out. Ambiguity may compensate for decision-making behavior in the traditional hierarchical analysis approaches that do not take uncertainties, ambiguities, and lack of information into consideration, making it possible to reflect the environment of the real world. In the subsequent analysis, FANP was used to compute the relative weight of items at every hierarchy, whereby the priority of every IC packaging R&D solution was evaluated as the basis for selection.

Application of fuzzy pair-wise comparison matrix

As mentioned earlier, defuzzification aims to address the uncertainty of the experts' subjective suggestions using the following steps: 1) transform the pair-wise comparison matrix of each expert into a fuzzy pair-wise comparison matrix; 2) combine these fuzzy pair-wise comparison matrices into a single fuzzy pair-wise comparison matrix; and 3) defuzzify to obtain the relative weight of individual criteria and sub-criteria. As an example, consider the TM dimension in the second hierarchy of Figure 2. Assuming there are 2 experts, the pair-wise comparison matrices of the 1st and 2nd experts are separately transformed into corresponding fuzzy pair-wise comparison matrices, as shown in Tables 3 and 4. After computing the fuzzy pair-wise comparison matrix of individual expert suggestion (Tables 3 and 4), combine the two fuzzy pair-wise comparison matrices into the fuzzy pair-wise comparison matrix of the expert group using the geometric average method (Table 5). Then, defuzzify the weight (the approximate value of the eigenvector) of the calculating level using the center of gravity equation (Hsieh et al., 2004), with the computed weight of the two experts' suggestions listed in Table 6. Finally, substitute the approximate value of the eigenvector

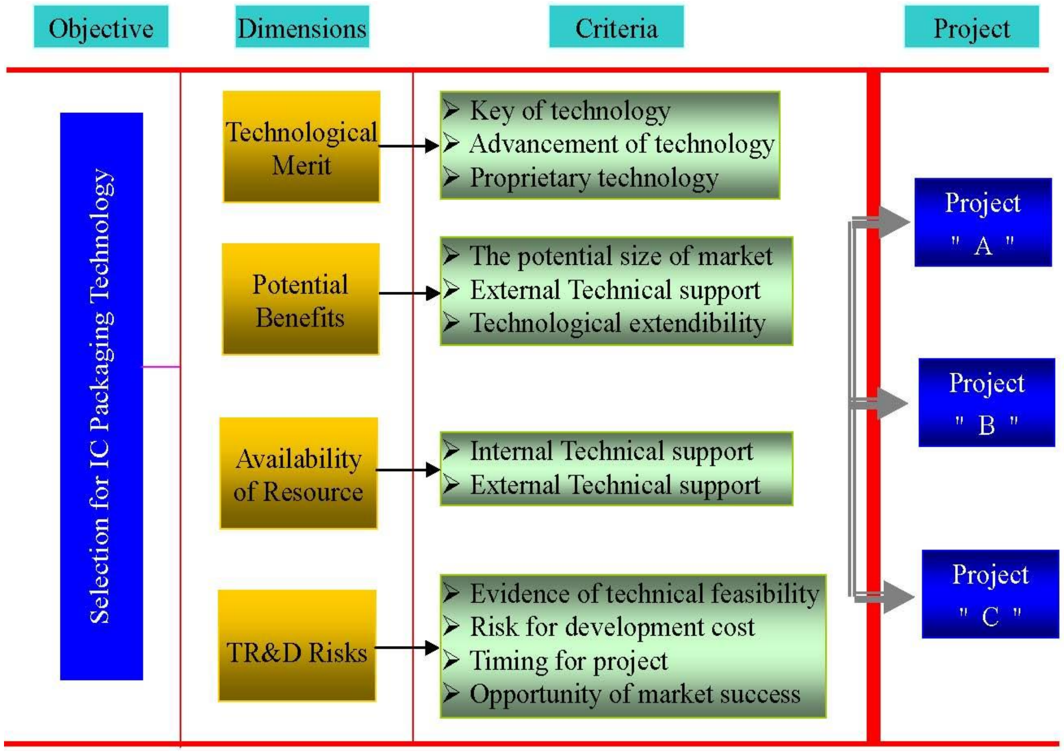

Figure 2. The ANP structure of control for IC packaging R&D.

Table 3. The first expert's fuzzy pair-wise comparison matrix transformation.

	Key of technology	Advancement of technology	Proprietary technology			Key of technology	Advancement of technology	Proprietary technology
Key of technology	1	1/2	1/4		Key of technology	(1, 1, 1)	(1/3, 1/2, 1)	(1/5, 1/4, 1/3)
Advancement of technology	2	1	1/3	➡	Advancement of technology	(1, 2, 3)	(1, 1, 1)	(1/4, 1/3, 1/2)
Proprietary technology	4	3	1		Proprietary technology	(3, 4, 5)	(2, 3, 4)	(1, 1, 1)

λ_{max}, 3.0183; C.I, 0.0092; C.R, 0.016.

Table 4. The second expert's fuzzy pair-wise comparison matrix transformation.

	Key of technology	Advancement of technology	Proprietary technology			Key of technology	Advancement of technology	Proprietary technology
Key of technology	1	3	3		Key of technology	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)
Advancement of technology	1/3	1	2	→	Advancement of technology	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 2, 3)
Proprietary technology	1/3	1/2	1		Proprietary technology	(1/4, 1/3, 1/2)	(1/3, 1/2, 1)	(1, 1, 1)

Table 5. Combined fuzzy pair-wise comparison matrix for two experts.

	Key of technology	Advancement of technology	Proprietary technology
Key of technology	(1, 1, 1)	(4/5, 11/9, 2)	(5/8, 6/7, 7/6)
Advancement of technology	(1/2, 9/11, 5/4)	(1, 1, 1)	(1/2, 4/5, 11/9)
Proprietary technology	(6/7, 7/6, 8/5)	(9/11, 5/4, 2)	(1, 1, 1)

in Table 6 into the super-matrix of ANP, thereby obtaining the weight of dimension and criteria at the final level.

Operation of the super-matrix

Firstly, construct the fuzzy pair-wise comparison matrices of the 44 experts according to the steps specified earlier, and compute the approximate eigenvector of controller IC packaging R&D hierarchy. As shown in Table 7, the weights of various hierarchies are combined into an unweighted super-matrix, which is used in super-matrix operation to obtain the weight of the controller IC packaging R&D project (Table 8). If the weighted super-matrix cannot meet the column-stochastic requirement in the calculating process, the super-matrix in Table 8 is given different weights for limiting until the various dimensions and criteria are converged, that is, the sum of each column is 1.

Table 9 shows the super-matrix after 27 applications of limiting (M^{27}). After the weights of the limiting super-matrix are normalized, it is possible to obtain the weights of various items in the criterion hierarchy as shown in Figure 3.

RESULTS

A controller IC is the key electronic component of our object of study, the micro HDD with 20GB storage. It reduces mechanical shock, provides read head control, and is responsible for the performance and effectiveness of the micro HDD. Control in the vertical dimension (Z-axis) of the controller IC is crucial, owing to the limited space in a micro HDD. For the controller IC packaging, the ratio of chip area to package area is close to more than 1.14 when chip scale package (CSP) is applied. This ratio approaches the ideal value of unity. However, this challenge will result in warpage of the components or destruction of the shape of the components and finally deteriorate the quality of the controller IC. In fact, the warpage of a micro HDD affects the manufacturing process yield of the controller IC. When the total height of the package is limited to 0.65 mm (Figure 4) and the warpage limit is less than 3 mil (Figure 5). With the selection of different combinations of substrate thickness and mold thickness, coefficient of thermal expansion (CTE) mismatch will occur in thermal processes during assembly. These include molding, post-mold curing and re-flow processes. In addition, different combinations can result in large variations in the

Table 6. Defuzzificated fuzzy pair-wise comparison matrix.

	Key of technology	Advancement of technology	Proprietary technology	Approximate value of eigenvector
Key of technology	1	4/3	8/9	0.3508
Advancement of technology	3/4	1	6/7	0.2862
Proprietary technology	9/8	7/6	1	0.3629

λ_{max}, 3.007; C.I, 0.0035; C.R, 0.006.

Table 7. Unweighted super-matrix.

		Dimension				Criteria										Objective		
		Technological merit	Availability of resource	Potential benefits	TR&D risks	Internal technical support	External technical support	Proprietary technology	Opportunity of market success	Risk for development cost	The potential size of market	Technological extendibility	Advancement of technology	Evidence of technical feasibility	Effects of patents technology	Timing for project	Key of technology	Selection for IC packaging technology
Dimensions	Technological merit	0.262	0.228	0.212	0.202	0	0	0	0	0	0	0	0	0	0	0	0	0.154
	Availability of resource	0.202	0.3	0.281	0.443	0	0	0	0	0	0	0	0	0	0	0	0	0.237
	Potential benefits	0.286	0.134	0.16	0.159	0	0	0	0	0	0	0	0	0	0	0	0	0.337
	TR&D risks	0.251	0.339	0.348	0.196	0	0	0	0	0	0	0	0	0	0	0	0	0.272
Criteria	Internal technical support	0	0.799	0	0	0.125	0.139	0.08	0.076	0.076	0.083	0.009	0.079	0.074	0.077	0	0.083	0
	External technical support	0	0.201	0	0	0.061	0.057	0.08	0.076	0.076	0.083	0.009	0.079	0.074	0.077	0	0.083	0
	Proprietary technology	0.44	0	0	0	0.082	0.08	0.101	0.076	0.076	0.083	0.009	0.151	0.074	0.077	0	0.082	0
	Opportunity of market success	0	0	0	0.223	0.082	0.08	0.08	0.072	0.124	0.083	0.009	0.079	0.105	0.077	0.2	0.083	0
	Risk for development cost	0	0	0	0.155	0.082	0.08	0.08	0.085	0.085	0.083	0.009	0.079	0.08	0.077	0.049	0.083	0
	The potential size of market	0	0	0.326	0	0.082	0.08	0.08	0.076	0.076	0.085	0.302	0.079	0.074	0.077	0	0.083	0
	Technological extendibility	0	0	0.439	0	0.082	0.08	0.08	0.076	0.076	0.085	0.314	0.079	0.074	0.158	0	0.083	0
	Advancement of technology	0.24	0	0	0	0.082	0.08	0.063	0.076	0.076	0.083	0.009	0.079	0.074	0.077	0	0.078	0
	Evidence of technical feasibility	0	0	0	0.414	0.082	0.08	0.08	0.074	0.119	0.083	0.009	0.079	0.165	0.077	0.204	0.083	0
	Effects of patents technology	0	0	0.235	0	0.082	0.08	0.08	0.076	0.076	0.083	0.3	0.079	0.074	0.073	0	0.083	0
	Timing for project	0	0	0	0.209	0.082	0.08	0.08	0.162	0.066	0.083	0.009	0.079	0.057	0.077	0.105	0.083	0
	Key of technology	0.32	0	0	0	0.082	0.08	0.118	0.076	0.076	0.083	0.009	0.061	0.074	0.077	0	0.093	0
Objective	Selection for IC packaging technology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total		2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 8. Weighted super-matrix.

		Dimension				Criteria												Objective
		Technological merit	Availability of resource	Potential benefits	TR&D risks	Internal technical support	External technical support	Proprietary technology	Opportunity of market success	Risk for development cost	The potential size of market	Technological extendibility	Advancement of technology	Evidence of technical feasibility	Effects of patents technology	Timing for project	Key of technology	Selection for IC packaging technology
Dimensions	Technological merit	0.131	0.114	0.106	0.101	0	0	0	0	0	0	0	0	0	0	0	0	0.154
	Availability of resource	0.101	0.15	0.14	0.222	0	0	0	0	0	0	0	0	0	0	0	0	0.237
	Potential benefits	0.143	0.067	0.08	0.079	0	0	0	0	0	0	0	0	0	0	0	0	0.337
	TR&D risks	0.125	0.17	0.174	0.098	0	0	0	0	0	0	0	0	0	0	0	0	0.272
Criteria	Internal technical support	0	0.4	0	0	0.125	0.139	0.08	0.076	0.076	0.083	0.009	0.079	0.074	0.077	0	0.083	0
	External technical support	0	0.101	0	0	0.061	0.057	0.08	0.076	0.076	0.083	0.009	0.079	0.074	0.077	0	0.083	0
	Proprietary technology	0.22	0	0	0	0.082	0.08	0.101	0.076	0.076	0.083	0.009	0.151	0.074	0.077	0	0.082	0
	Opportunity of market success	0	0	0	0.111	0.082	0.08	0.08	0.072	0.124	0.083	0.009	0.079	0.105	0.077	0.2	0.083	0
	Risk for development cost	0	0	0	0.077	0.082	0.08	0.08	0.085	0.085	0.083	0.009	0.079	0.08	0.077	0.049	0.083	0
	The potential size of market	0	0	0.163	0	0.082	0.08	0.08	0.076	0.076	0.085	0.302	0.079	0.074	0.077	0	0.083	0
	Technological extendibility	0	0	0.22	0	0.082	0.08	0.08	0.076	0.076	0.085	0.314	0.079	0.074	0.158	0	0.083	0
	Advancement of technology	0.12	0	0	0	0.082	0.08	0.063	0.076	0.076	0.083	0.009	0.079	0.074	0.077	0	0.078	0
	Evidence of technical feasibility	0	0	0	0.207	0.082	0.08	0.08	0.074	0.119	0.083	0.009	0.079	0.165	0.077	0.204	0.083	0
	Effects of patents technology	0	0	0.117	0	0.082	0.08	0.08	0.076	0.076	0.083	0.3	0.079	0.074	0.073	0	0.083	0
	Timing for project	0	0	0	0.104	0.082	0.08	0.08	0.162	0.066	0.083	0.009	0.079	0.057	0.077	0.105	0.083	0
	Key of technology	0.16	0	0	0	0.082	0.08	0.118	0.076	0.076	0.083	0.009	0.061	0.074	0.077	0	0.093	0
Objective	Selection for IC packaging technology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

warpage level. The product development and key technologies of the HDD controller IC involve the substrate and lens thickness manufacturing technologies. For example, using the lower cost substrate of relatively higher thickness (0.136 mm) as the base would result in a more favorable hardness. However, given the product’s height limit of 0.65 mm, thinner lenses of 1.5 mil need to be fabricated. Warpage is relatively low at 1.56 mil as evidenced by the simulation software. However, the manufacturing process and quality control becomes increasingly difficult and

Table 9. Limiting super-matrix.

		Dimension				Criteria												Objective
		Technological Merit	Availability of Resource	Potential Benefits	TR&D Risks	Internal Technical support	External Technical support	Proprietary technology	Opportunity of market success	Risk for development cost	The potential size of market	Technological extendibility	Advancement of technology	Evidence of technical feasibility	Effects of patents technology	Timing for project	Key of technology	Selection for IC Packaging Technology
Dimensions	Technological merit	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Availability of resource	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Potential benefits	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	TR&D risks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Criteria	Internal technical support	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072
	External technical support	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062	0.062
	Proprietary technology	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071
	Opportunity of market success	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088	0.088
	Risk for development cost	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106	0.106
	The potential size of market	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096
	Technological extendibility	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105	0.105
	Advancement of technology	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
	Evidence of technical feasibility	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094	0.094
	Effects of patents technology	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095
	Timing for project	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078
	Key of technology	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Objective	Selection for IC packaging technology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

complicated as the lens becomes thinner. This leads to additional manufacturing time and an increased risk in the development process. In contrast, if a relatively thicker lens (for example, 3.5 mil) is used, the development process can be completed in less time. However, as the thickness of the substrate is only 0.2 mm, the control of warpage will become more difficult due to insufficient substrate thickness and hardness, as well as the influence of the molding process, leading to damage to the lens properties. To summarize, lens thickness not only affects the development of lens manufacturing technologies, but also directly influences the sizes of the mold compound. Additionally, different combinations may differ greatly in terms of their effect on the warpage of the HDD controller IC, as well as directly affecting the marketing time and cost of the product. This study analyzed the R&D project selection of a controller IC for a micro HDD packaging process, and designed three possible manufacturing processes (Table 10) using finite element method (FEM) and Taguchi methods. Using the desirability index, it is hoped that these three manufacturing processes could be integrated into projects with network hierarchies, thereby enabling executives to determine the optimal packaging project for R&D under the existing state of operation. In this paper, the four dimensions and twelve criteria in Figure 2 were

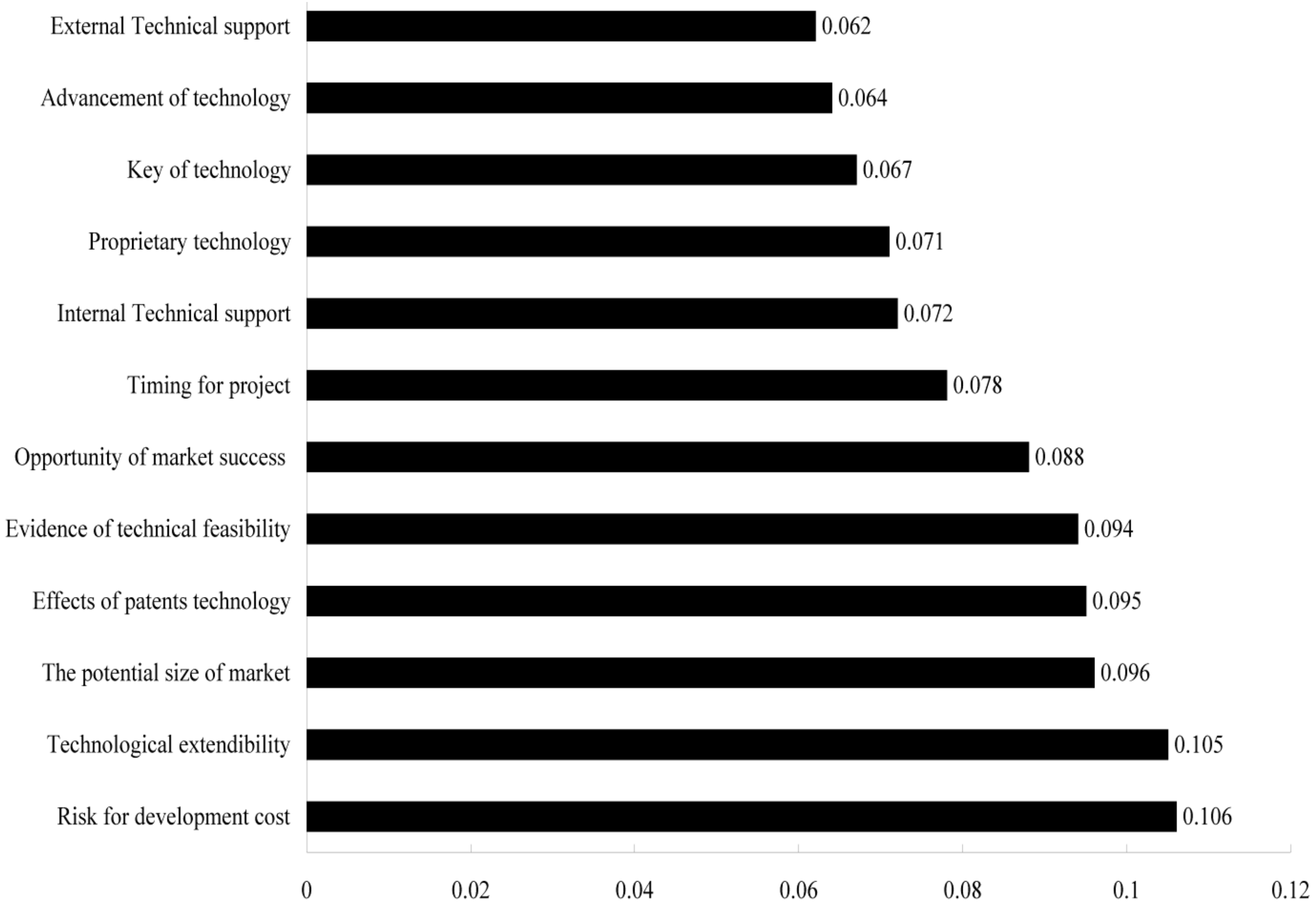

Figure 3. Criteria priority for controller IC packaging process R&D.

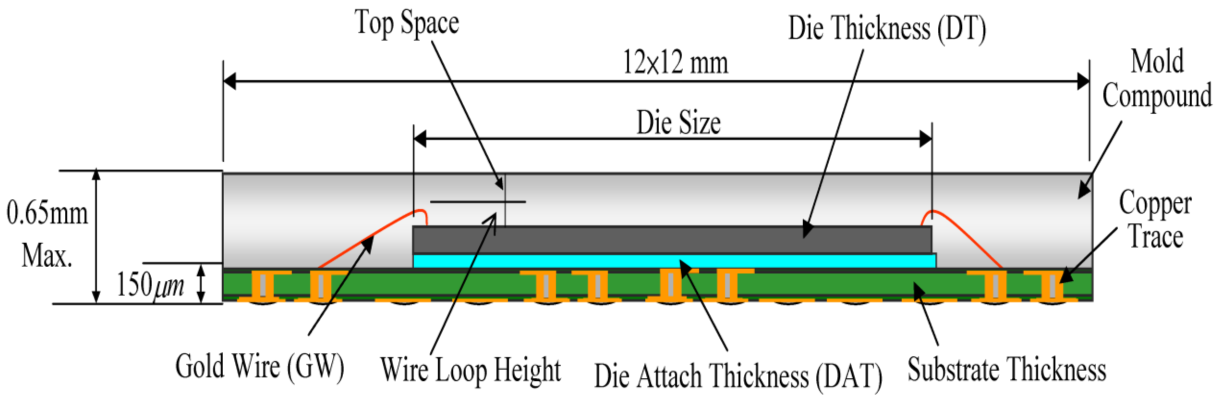

Figure 4. Controller IC package for micro HDD.

taken as the evaluation benchmark, and the three packaging projects in Table 10 were compared. The process, as described earlier is to construct a fuzzy pair-wise comparison matrix according to fuzzy theory, combine the questionnaire for expert groups with Equation 4, and then obtain the fuzzy pair-wise comparison matrix of expert groups. Following this, defuzzify the fuzzy pair-wise comparison matrix using the center of gravity Equation 5, computing the weights of the three scenarios (Table 11) and testing the consistency of λ_{max}, C.I and

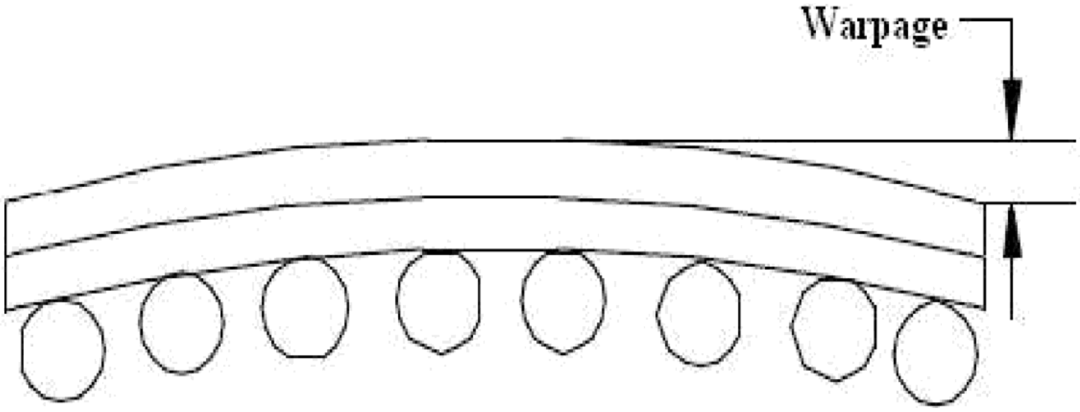

Figure 5. Convex warpage, bent downward.

Table 10. Projects for controller IC packaging R&D.

	Project "A"	Project "B"	Project "C"
Pkg.	UTLGA 12×12/172	XTLGA 12×12/172	XTLGA 12×12/172
Substrate	BT, 0.136mm	BT, 0.106mm	BT, 0.09mm
Mold thickness	0.3mm	0.25mm	0.2mm
Die size	5.2×5.2mm	5.2×5.2mm	5.2×5.2mm
Die thickness	1.5mil	2.5mil	3.5mil
Film	EM-500 M3, 25um thick	EM-500 M3, 25um thick	EM-500 M3, 25um thick
Compound	Kyocera KE-1150 UM	Kyocera KE-1150 UM	Kyocera KE-1150 UM
warpage predicts	1.56mil	2.78mil	3mil

C.R. According to the computed results in Table 11, the weight of Projects "A", "B", and "C" are substituted into Equation 3, and the relative weight and DI of three manufacturing packages are computed as shown in Table 12. Among the expected value of these manufacturing processes, Project "A" (DI_A = 0.025+ 0.012+ 0.019+ 0.039+ 0.021+ 0.044+ 0.027+ 0.02+ 0.043+ 0.048+ 0.023+ 0.03= 0.351) has the highest weight, followed by Project "B"(0.329) and Project "C"(0.32). The analytical results show that the priority of consideration should be given to scenario A during the controller IC packaging R&D project selection.

CONCLUSION AND DISCUSSION

This study is the first to apply FANP model to evaluate the strategic impact of new IC manufacturing technologies. Although, there are some related works dealing with similar topic, which we have mentioned in literature section, the methodologies applied in the mentioned research are different from ours. As a result of the FANP analysis, the following priorities are given by DI, as for the alternative: Project "A" (0.351) > Project "B" (0.329) > Project "C" (0.32). The results indicate that the selection for the R&D project should be 1) lower risk for development cost (Substrate: 0.136 mm and mold thickness: 0.3 mm), 2) technological extendibility and potential size of the market (Die thickness: 1.5 mil and film: 25 um). Since there is a large variation of CTE characteristics among different mold thickness and mold compound types, as well as substrate thickness and mold thickness, selecting the proper combination of the aforementioned four variables is essential to control the warpage level (warpage predicts: 1.56 mil). Lens thickness not only affects the development of lens manufacturing technologies, but also directly influences their time-to-market and relative cost. Our case study summarized the four dimensions and twelve criteria of the HDD controller IC project through interviews with experts, and constructed an ANP network using the dependency relationship of dimensions and criteria. The study determined the key decision-making factors for R&D project selection using FANP, proposed three packaging projects in cooperation with the sample company, and combined them into an optimal manufacturing process by calculating the desirability index.

During controller IC packaging R&D selection, five leading items associated with packaging R&D were obtained from FANP, namely: 1) risks for development cost

Table 11. Pair-wise comparison matrix for controller IC packaging R&D projects.

Criteria	Project	Weight	λ_{max}	C.I	C.R
Key of technology	A	0.368	3.015	0.007	0.013
	B	0.326			
	C	0.306			
Advancement of technology	A	0.187	3.019	0.01	0.016
	B	0.356			
	C	0.456			
Proprietary technology	A	0.273	3.002	0.001	0.002
	B	0.386			
	C	0.341			
The potential size of market	A	0.402	3.050	0.025	0.043
	B	0.222			
	C	0.376			
Effects of patents technology	A	0.218	3.005	0.003	0.004
	B	0.347			
	C	0.435			
Technological extendibility	A	0.42	3.087	0.044	0.075
	B	0.344			
	C	0.235			
Internal technical support	A	0.377	3.061	0.030	0.052
	B	0.378			
	C	0.246			
External technical support	A	0.32	3.006	0.003	0.006
	B	0.351			
	C	0.328			
Evidence of technical feasibility	A	0.455	3.115	0.057	0.099
	B	0.304			
	C	0.241			
Risk for development cost	A	0.449	3.113	0.057	0.097
	B	0.299			
	C	0.252			
Timing for project	A	0.297	3.003	0.002	0.003
	B	0.289			
	C	0.415			
Opportunity of market success	A	0.339	3.079	0.039	0.068
	B	0.384			
	C	0.277			

(0.106); 2) technological extendibility (0.105); 3) the potential size of the market (0.096); 4) effects of patents technology (0.095); and 5) evidence of technical feasibility (0.094). In other words, the company should attach great importance to possible risks on packaging R&D, such as a shortage of resources and labor force, time wasting, and so on. The company should then consider the potential benefits of a R&D project, such as the possible profitability of technological extendibility, potential market scale and manufacturability.

Finally, the company should take into consideration the project’s technical feasibility. We conclude that project

Table 12. Desirability calculation for controller IC packaging R&D project scenarios.

Criteria	Project	Weight	Criteria	Scenario	Weight
Key of technology (0.067)	A (0.368)	0.025	Internal technical support (0.072)	A(0.377)	0.027
	B (0.326)	0.022		B(0.378)	0.027
	C (0.306)	0.021		C(0.246)	0.018
Advancement of technology (0.064)	A (0.187)	0.012	External technical support (0.062)	A(0.32)	0.02
	B (0.356)	0.023		B(0.351)	0.022
	C (0.456)	0.029		C(0.328)	0.02
Proprietary technology (0.071)	A (0.273)	0.019	Evidence of technical feasibility (0.094)	A(0.455)	0.043
	B (0.386)	0.027		B(0.304)	0.029
	C (0.341)	0.024		C(0.241)	0.023
The potential size of market (0.096)	A (0.402)	0.039	Risk for development cost (0.106)	A(0.449)	0.048
	B (0.222)	0.021		B(0.299)	0.032
	C (0.376)	0.036		C(0.252)	0.027
Effects of patents technology (0.095)	A (0.218)	0.021	Timing for project (0.078)	A(0.297)	0.023
	B (0.347)	0.033		B(0.289)	0.023
	C (0.435)	0.041		C(0.415)	0.032
Technological extendibility (0.105)	A (0.42)	0.044	Opportunity of market success (0.088)	A(0.339)	0.03
	B (0.344)	0.036		B(0.384)	0.034
	C (0.235)	0.025		C(0.277)	0.024

"A" is an optimum solution in terms of implementation feasibility.

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