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A fuzzy AHP application in government-sponsored R&D project selection☆

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Abstract

Due to the funding scale and complexity of technology, the selection of government sponsored technology development projects can be viewed as a multiple-attribute decision that is normally made by a review committee with experts from academia, industry, and the government. In this paper, we present a fuzzy analytic hierarchy process method and utilize crisp judgment matrix to evaluate subjective expert judgments made by the technical committee of the Industrial Technology Development Program in Taiwan. Our results indicate that the scientific and technological merit is the most important evaluation criterion considered in overall technical committees. We demonstrate how the relative importance of the evaluation criteria changes under various risk environments via simulation.

Keywords: Fuzzy analytic hierarchy process; Government sponsored R&D projects; Crisp judgment matrix; Simulation

1. Introduction

Technology is viewed as one of the major factors determining the competitiveness of an industry. Private firms may not pursue technology research and development (R&D) projects because: (1) R&D scientific and technical frontiers are risky and the chances of failure are high. (2) An individual firm may not have the capabilities required to develop the technology. And (3) private incentives may not be sufficient to induce a firm to undertake the project in the face of difficulties in appropriating the resulting benefits [1]. In many countries, government-sponsored R&D programs prove to be a useful strategy to encourage private firms to undertake R&D projects [2]. For example, the American government initiated the Advanced Technology Program (ATP) in 1990 to encourage industry to develop technology projects. ATP has approved 134 R&D projects and totally funds committed US$331 million between 2002 and 2004 [3]. Korea, Japan, China, and many other organization for economic cooperation and development (OECD) countries have all launched advanced technology programs to encourage private firms to develop core technologies and to secure cutting-edge technologies.

Taiwan launched similar government-sponsored technology development programs (TDP) in 1979, such as the Industrial Technology Development Program (ITDP), the Small Business Innovation Program

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(SBIR), etc. The research budget of the TDP has steadily increased [4]. For example, TDP's actual expenditure increased from NT$15.17 billion to NT$18.22 billion from 2001 to 2004. Also manpower devoted to the corporation increased from 5561.2 person/year in 1999 to 6644.9 person/year in 2003. The TDP produced 797 patents, 450 patent applications, 1061 technology transfers, 2190 technical papers, 622 subcontracted research projects, and 1595 contracts and industrial services in 2003 [5]. With respect to the benefits of R&D, the TDP also produced 618 enterprise investments [5].

As governments strive to become more efficient and reduce the costs of services in order to remain competitive, the choice of government-sponsored TDP projects has become increasingly important [6]. Due to the funding scale and complexity of technology, the selection of TDP projects can be viewed as a multiple-attribute decision that is normally made by a review committee with experts from academia, industry, and the government. However, these experts, who have a diversity of knowledge, often enter the group with different assumptions, viewpoints, and interpretations of the issues involved and often select proposed TDP projects based on evaluation criteria that are not clearly defined. Therefore, review committees tend to select projects with consensus. An effective mechanism to resolve this kind of cognitive conflict is necessary.

Many published studies on R&D portfolio selection have developed a wide variety of models related to experts' judgments [7–9]. Perrone [10] used the fuzzy multiple criteria decision model (fuzzy MCDM) to evaluate advanced manufacturing systems. Coffin and Taylor [11] first presented multiple criteria R&D project selection using fuzzy logic, then a few pioneering studies, e.g., Chan et al. [12] and Hsu et al. [6], formulated their theoretical frameworks based on fuzzy multiple criteria method[1] to analyze technology project selection. In this paper we integrate previous research findings and use a theoretical approach, which is based on a fuzzy version of analytic hierarchy process (fuzzy AHP) to help in government-sponsored R&D project selections.

Unlike R&D project selection in private firms, the selection process of government-sponsored R&D projects is less discussed [6]. Wang et al. [13] indicated that evaluation criteria at national level R&D project selection is difficult to find. Zhang et al. [14] also indicated that establishing a proper evaluation system of criteria is the basis for technology R&D projects. However, Bilalis et al. [15] indicated that certain objective goals and criteria are difficult to measure with distinct values in project selection. It is crucial to establish a proper system to identify criteria and find the relative importance of criteria for selecting government-sponsored R&D projects. As Henriksen and Traynor [16] noted, the purpose of weighting is not only to emphasize the most appropriate criteria, but also to facilitate self-selection of the optimal R&D portfolio. Thus, different from Hsu et al.'s approach, which employs a fuzzy number for scoring technology alternatives, we use fuzzy numbers to score judgments of evaluation criteria.

Computational steps of fuzzy AHP need to formulate a judgment matrix. Some studies [17,23,19] employed α-cuts and convex combinations to form a crisp judgment matrix and others [20,21,6] employed α-cuts to create a fuzzy judgment matrix. Unlike previous studies in government-sponsored R&D project selections [6,13], we use a crisp judgment matrix, incorporated with the index of optimism, to deal with criteria weighting and simulate important changes of criteria under various decision risks.

In order to put later discussions in perspective, we first offer a brief description of ITDP project selection in Taiwan. This includes challenges to R&D project selection decisions. We discuss a fuzzy AHP approach, which includes a group decision-making method to develop a hierarchical structure for ITDP project selection, in-depth interviews of the ITDP review committees to obtain their evaluating criteria, and a triangular fuzzy number for scoring these experts' judgments. We further detail the fuzzy AHP findings about the managerial perceptions by simulating the risk attitude of these committees. We then outline the policy implications of our findings, followed by conclusions.

2. ITDP project selection in Taiwan: a background

The ITDP, the emphasis of our research, is one of the major technology development programs in Taiwan. The aim of the ITDP is to encourage industries to take part in key innovative technologies and applied research. The ITDP supports industrial R&D projects in four main areas: telecommunication and electronics, mechanical engineering and aeronautics, materials and chemical engineering, and biotechnology and pharmaceuticals. According to official data, 588 applications have been filed and 259 (44%) of them have been approved since 1999. Table 1 shows ITDP investment from 1999 to 2004. Among the 259 sponsored projects, material and chemical engineering-based projects (38%) and machinery and aerospace-based projects (38%)

[1] There was considerable empirical support for fuzzy multiple criteria methods, and researchers have suggested various ways to broaden their applicability [17,20–24].

Table 1
ITDP investment (1999/02–2004/12)

Project areas	No. of projects	Percentage of subsidized cases	Government subsidy[a]	Company R&D expenditure[a]
Telecommunication and electronics	117	36%	38.92	106.49
Mechanical engineering and aeronautics	47	38%	16.56	49.83
Materials and chemical engineering	60	38%	11.42	37.85
Biotechnology and pharmaceutical	35	36%	6.98	18.85
Total	259	37%	73.88	213.02

[a]Unit: hundred million NT$.

account for the largest segment. From 1997 to 2004, the ITDP's actual expenditure increased significantly from NT$2.85 billion to NT$29 billion. The ITDP has produced 236 patents, 472 applied patents, 1786 technical reports and held 201 technical conferences. Furthermore, the ITDP has contributed NT$634.35 million for technology and NT$761.47 million for industry, academia and research collaboration [5].

According to the Department of Industrial Technology (DOIT), there are 38 experts in the ITDP technical advisory committee. The committee includes seven directors from four public research institutes and 31 professors from 11 universities. The ITDP project evaluation involves two steps. According to decision criteria given by the DOIT, three to five experts with domain knowledge in each project arena will first independently review the technical feasibility and the expected returns of ITDP applications. Technical uncertainties, market risks, and the lack of hard data are reasons why the evaluation usually proceeds subjectively and intuitively. The final approval/disapproval decision will then be made by the overall 38 experts from all four areas in the regular technical advisory committee meetings. Since the committee involves experts from various domains, divergent judgments must be taken into account. Thus, the committee, according to decision criteria by the DOIT, tends to make decisions in a consensus way with a degree of compromise.

3. R&D project selection

R&D project selection involves multiple interrelated criteria, resources and uncertain and qualitative factors that are difficult to measure. Many R&D project selection models and techniques, including qualitative and quantitative approaches, appear in literature for R&D project selection. These selection models include mathematical models, financial models, checklist models, scoring models, decision theory models, consensus models, and portfolio models [7–9,16,25,26]. Even with the large number of proposed models, the R&D selection problem remains problematic and few models have gained wide acceptance [27]. The results of Liberatore and Titus [8] showed mathematical models such as linear and integer programming methods are not commonly used in industry because of the diversity of project types, resources and criteria used. They also found that most companies use one or more traditional financial approaches to estimate project returns. Although financial models utilize tangible or monetary aspects to evaluate R&D projects, the some projects may include non-monetary criteria that are difficult to quantify.

Meade and Presley [27] revealed four major themes for R&D project selection: (1) The need to relate selection criteria to corporate strategies. (2) The need to consider qualitative benefits and risks of proposed projects. (3) The need to reconcile and integrate the needs and desires of different stakeholders. And (4) the need to consider the multi-stage and group decision processes. Limitations of existing R&D project selection models are: (1) Inadequate treatment of multiple, often interrelated, evaluation criteria. (2) An inability to handle non-monetary aspects and inadequate treatment of interrelationships among projects. (3) No explicit recognition and incorporation of the experience and knowledge of R&D managers. And (4) perceptions by R&D managers that these models are difficult to understand and use [28].

Most research on R&D project selection concentrates on the private sector while little research has been done on government-sponsored R&D projects [6]. Hsu et al. [6] and Kutlaca [29] noted that government-sponsored R&D projects differ from those of the private sector in four major aspects: (1) Government-sponsored R&D is by nature a strategic and long-term investment. Thus, conventional financial justification approaches are probably inadequate. (2) Political factors and interested parties always influence the allocation of R&D resources in the public sector. (3) The difficulty in selecting the

R&D projects is increased because of the ambiguity of innovative technology and the lack of experts. And (4) R&D requires technique and is influenced by government policies.

Analytic Hierarchy Process (AHP) [30] is one of the most popular and powerful methods for group decision-making used in project selection [31]. For decisions in government-sponsored R&D projects, e.g., ITDP, the criteria are difficult to quantify and evaluate. Instead of using exact numbers, phrases like "much more important than" can be used to extract the decision-makers' preferences. Fuzzy set theory, first proposed by Zadeh [32], and the subsequent fuzzy decision-making methods [33] offer a more natural way of dealing with these preferences instead of exact values. The use of fuzzy numbers and linguistic terms is more suitable since the traditional AHP approach is somewhat arbitrary. The traditional AHP employs exact numbers such as 1–9 to score. However, much decision-making involves some uncertainty [34]. The traditional AHP does not take into account the uncertainty associated with the mapping of one's perception (or judgment) to a number [18]. Lee [19] indicated that fuzzy numbers are preferable to extend the range of the crisp decision matrix in the classical AHP method insofar as human judgment is never precise. Besides, one of the most important aspects for a useful decision aid is to provide the ability to handle imprecise and vague information [14]. Therefore, Chen [35] expressed that fuzzy set theory provides us with a useful tool to deal with the ambiguity involved in the data evaluation process. Several theoretical results have been presented as the application of fuzzy set theory in analytic hierarchy process [17,20,22,24,36]. The fuzzy AHP is thus suitable for the decision of government-sponsored R&D project selection.

4. A fuzzy analytic hierarchy framework for R&D project section

4.1. Essences of fuzzy AHP

AHP is a useful approach for evaluating complex multiple criteria alternatives involving subjective judgment. A decision-maker determines his or her weights by conducting pair-wise comparisons between criteria. Though the aim of AHP is to capture a decision-maker's knowledge, the conventional AHP cannot fully reflect the human thinking style. Linguistic and vague descriptions could not be solved easily by AHP until the recent development in fuzzy decision-making [37]. Fuzzy pair-wise comparisons are more rational to represent decision-makers' uncertain judgments than crisp ones [38]. In ITDP selection, due to the availability and uncertainty of information, it is hard for decision-makers to obtain precise data for making judgments. Most decision-makers tend to give assessments based on their knowledge, past experience and subjective judgments [12]. In general, linguistic variables such as "very important" or "very unimportant" are used to convey ITDP expert's assessments. Fuzzy set theory, resembling human reasoning in its use of approximate information and certainty to generate decisions, is a better approach to convert linguistic variables to fuzzy numbers under ambiguous assessments [39]. By incorporating fuzzy set theory with AHP, fuzzy AHP allows a more accurate description of the decision-making process. The earliest work in fuzzy AHP presented in Laarhoved and Pedrycz [36], compared fuzzy ratios described with triangular membership functions. Many studies for fuzzy AHP are proposed [17,20–22,24].

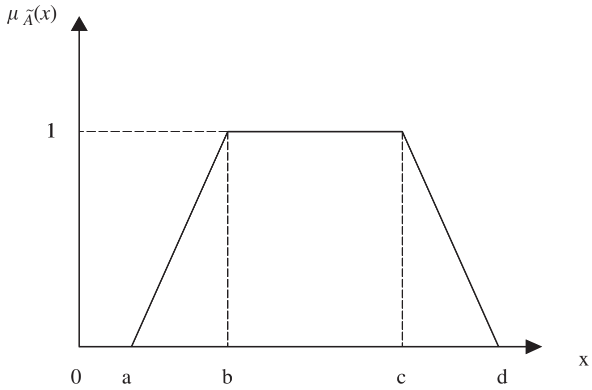

Fig. 1. The trapezoidal-type membership function.

A fuzzy number is a special fuzzy set $F = \{(x, \mu_f(x)), x \in R\}$, $R : -\infty < x < \infty$, and its membership function $\mu_f(x) : R[0, 1]$, where x represents the ITDP projects. A trapezoidal fuzzy number is denoted as $\tilde{M} = (a, b, c, d)$, where $a \leqslant b \leqslant c \leqslant d$, has the following trapezoidal-type membership function 1 and Fig. 1:

$$\mu_{\tilde{M}}(x) = \begin{cases} 0 & x < a, \\ \dfrac{x-a}{b-a} & a \leqslant x \leqslant b, \\ 1 & b < x \leqslant c, \\ \dfrac{d-x}{d-c} & c < x \leqslant d, \\ 0 & d < x. \end{cases} \tag{1}$$

When $b = c$, the triangular fuzzy number (TFN) is denoted as $\tilde{M} = (a, b, d)$, where $a \leqslant b \leqslant d$ has the triangular-type membership function. By defining the interval of confidence level α, the triangular fuzzy number can be described as

$\forall \alpha \in [0, 1]$,

$$\tilde{M}_\alpha = [a^\alpha, d^\alpha] = [(b-a)\alpha + a, -(d-b)\alpha + d].$$

Triangular fuzzy numbers, from $\tilde{1}$ to $\tilde{9}$ are used to represent subjective pair-wise comparisons in order to capture vagueness. By using triangular fuzzy numbers, via pair-wise comparison, the fuzzy judgment matrix is constructed.

In ITDP selection, we first use linguistic terms to represent the experts' assessments. For example, experts use 9 for "extremely important", 5 for "relatively important", and 1 for "extremely unimportant" for objectives/criteria such as "technology relevance" and "technology competitiveness." In addition, we utilize a set of triangular fuzzy numbers from 1 to 9 to represent their importance. A set of TFNs (8, 9, 10) for "extremely important", (4, 5, 6) for "relatively important", and (1, 1, 2) for "extremely unimportant", are used to capture the fuzzy range of experts' judgment. Thus, fuzzy AHP can be used to express subjective judgments of ITDP experts by pair-wise comparison matrix. Our computational procedure is described as follows.

4.2. Computational procedure of fuzzy AHP

Step 1: *Scaling the relative strength of the criteria and alternatives*. Pedrycz [40] expressed that a triangular function is the easiest way to approach the convex function and is the simplest to explain. Thus, triangular fuzzy numbers ($\tilde{1}$–$\tilde{9}$) are employed to indicate the relative strength of each criterion and alternative in the same hierarchy.

Step 2: *Computing the fuzzy judgment matrix*. Assume that there are K criteria $C_1, C_{2,\ldots,} C_K$ with a fuzzy judgment matrix $\tilde{A}_k$ for each C_k, $1 \leqslant k \leqslant K$. A decision-maker needs to supply pair-wise comparisons of criteria to produce a fuzzy judgment matrix $\tilde{E}$. The fuzzy judgment matrices $\tilde{A}_k(\tilde{a}_{ij})$ and $\tilde{E}(\tilde{e}_{ij})$ are computed by utilizing triangular fuzzy number via pair-wise comparisons as noted below

$$\tilde{A}_k = \begin{pmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1(n-1)} & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2(n-1)} & \tilde{a}_{2n} \\ \vdots & \vdots & & \vdots & \vdots \\ \tilde{a}_{(n-1)1} & \tilde{a}_{(n-1)1} & \cdots & 1 & \tilde{a}_{(n-1)n} \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{n(n-1)} & 1 \end{pmatrix},$$

where $i = j$, $a_{ij} = 1$; where $i \neq j$, $a_{ij} = \tilde{1} \sim \tilde{9}$, $\tilde{9}^{-1} \sim \tilde{1}^{-1}$

$$\tilde{E} = \begin{pmatrix} 1 & \tilde{e}_{12} & \cdots & \tilde{e}_{1(n-1)} & \tilde{e}_{1n} \\ \tilde{e}_{21} & 1 & \cdots & \tilde{e}_{2(n-1)} & \tilde{e}_{2n} \\ \vdots & \vdots & & \vdots & \vdots \\ \tilde{e}_{(n-1)1} & \tilde{e}_{(n-1)1} & \cdots & 1 & \tilde{e}_{(n-1)n} \\ \tilde{e}_{n1} & \tilde{e}_{n2} & \cdots & \tilde{e}_{n(n-1)} & 1 \end{pmatrix},$$

where $i = j$, $e_{ij} = 1$; where $i \neq j$, $e_{ij} = \tilde{1} \sim \tilde{9}$, $\tilde{9}^{-1} \sim \tilde{1}^{-1}$.

According to the analysis of Buckley [41], we assume that there are n decision-makers, $J_{1,\ldots,} J_n$. Each J_l gives a fuzzy judgment matrix $\tilde{A}_{kl}$ for each criterion C_k and supplies a fuzzy judgment matrix $\tilde{E}_l$ between criteria. Let $\tilde{A}_{kl} = \left[\tilde{a}_{ij}^{kl}\right]$ and $\tilde{E}_l = \left[\tilde{e}_{ij}^{l}\right]$. The average fuzzy judgment matrices $\tilde{A}_k = \left[\tilde{a}_{ij}^{k}\right]$ and $\tilde{E} = \left[\tilde{e}_{ij}\right]$ are computed as follows: $\tilde{a}_{ij}^{k} = \left(\tilde{a}_{ij}^{k1} \Theta \cdots \Theta \tilde{a}_{ij}^{kn}\right)^{1/n}$ and $\tilde{e}_{ij} = \left(\tilde{e}_{ij}^{1} \Theta \cdots \Theta \tilde{e}_{ij}^{n}\right)^{1/n}$.

Step 3: *Estimating the degree of optimism for* $\tilde{A}$ *and* $\tilde{E}$. Compute the degree of optimism for decision-makers by the index of optimism μ. The larger the index μ, the higher the degree of optimism. According to the analysis of Lee [19], the index of optimism is a linear convex combination as noted below

$$\tilde{a}_{ij}^{\alpha} = \mu a_{iju}^{\alpha} + (1-\mu) a_{ijl}^{\alpha} \quad \forall \mu \in [0, 1], \tag{2}$$

$$\tilde{e}_{ij}^{\alpha} = \mu e_{iju}^{\alpha} + (1-\mu) e_{ijl}^{\alpha} \quad \forall \mu \in [0, 1]. \tag{3}$$

While α is fixed, we set the index of optimism μ in order to estimate the degree of optimism and we can present the following crisp judgment matrices $\tilde{A}^*$ and $\tilde{E}^*$:

$$\tilde{A}^* = \begin{pmatrix} 1 & \tilde{a}_{12}^{\alpha} & \cdots & \tilde{a}_{1(n-1)} & a_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & 1 & \cdots & \tilde{a}_{2(n-1)}^{\alpha} & a_{2n}^{\alpha} \\ \vdots & \vdots & & \vdots & \vdots \\ \tilde{a}_{(n-1)1}^{\alpha} & \tilde{a}_{(n-1)1}^{\alpha} & \cdots & 1 & \tilde{a}_{(n-1)n}^{\alpha} \\ a_{n1}^{\alpha} & a_{n2}^{\alpha} & \cdots & \tilde{a}_{n(n-1)}^{\alpha} & 1 \end{pmatrix},$$

$$\tilde{E}^* = \begin{pmatrix} 1 & \tilde{e}_{12}^{\alpha} & \cdots & \tilde{e}_{1(n-1)} & e_{1n}^{\alpha} \\ \tilde{e}_{21}^{\alpha} & 1 & \cdots & \tilde{e}_{2(n-1)}^{\alpha} & \tilde{e}_{2n}^{\alpha} \\ \vdots & \vdots & & \vdots & \vdots \\ \tilde{e}_{(n-1)1}^{\alpha} & \tilde{e}_{(n-1)1}^{\alpha} & \cdots & 1 & \tilde{e}_{(n-1)n}^{\alpha} \\ \tilde{e}_{n1}^{\alpha} & \tilde{e}_{n2}^{\alpha} & \cdots & \tilde{a}_{n(n-1)}^{\alpha} & 1 \end{pmatrix}.$$

Step 4: *Solving fuzzy eigenvalue*. A fuzzy eigenvalue λ is a fuzzy number solution to

$$\tilde{A}^{*}\tilde{x}=\tilde{\lambda}\tilde{x}, \quad (4)$$

where $\tilde{A}$ is a n-by-n fuzzy matrix containing fuzzy number $\tilde{a}_{ij}$ and $\tilde{x}$ is a non-zero n-by-1 fuzzy eigenvector containing the fuzzy number $\tilde{x}_i$. Fuzzy multiplication and addition are performed by using interval arithmetic and α-cuts. Eq. (4) is equal to

$$\left[a_{i1l}^{\alpha}x_{1l}^{\alpha}, a_{i1u}^{\alpha}x_{1u}^{\alpha}\right] \oplus \cdots \oplus \left[a_{inl}^{\alpha}x_{nl}^{\alpha}, a_{inu}^{\alpha}x_{nu}^{\alpha}\right]=\left[\lambda x_{il}^{\alpha}, \lambda x_{iu}^{\alpha}\right], \quad (5)$$

where

$$\tilde{A}=[\tilde{a}_{ij}], \tilde{x}=(\tilde{x}_{1,\dots,}\tilde{x}_n),$$
$$a_{ij}^{\alpha}=\left[a_{ijl}^{\alpha}, a_{iju}^{\alpha}\right], \quad \tilde{x}_j=\left[x_{il}^{\alpha}, x_{iu}^{\alpha}\right], \quad \lambda_l^{\alpha}=\left[\lambda_l^{\alpha}, \lambda_u^{\alpha}\right] \quad (6)$$

for $0 \leqslant \alpha \leqslant 1$ and all i, j, where $i=1,2,\dots,n$, $j=1,2,\dots,n$.

Step 5: *Determining the weights for criteria and alternatives*. Compute the fuzzy weights $\tilde{w}_k=(\tilde{w}_{1k,\dots,}\tilde{w}_{nk})$ for $\tilde{A}_k^*$ and fuzzy weights $\tilde{e}=(\tilde{e}_{1,\dots,}\tilde{e}_K)$ for $\tilde{E}^*$. The eigenvector is computed by fixing the μ value and estimating the maximal eigenvalue.

Step 6: *Ranking the alternatives*. The fuzzy AHP ranks alternatives across all the criteria. After synthesizing the priorities over all hierarchy, the final fuzzy weights for alternative A_j are determined by varying α value. The ranking of the final alternatives is given by the vector $r^T=(r_{1,\dots,}r_n)$ where $r_j=\sum_{k=1}^{K} w_{ij}e_k$.

5. Evaluating hierarchical structure for ITDP selection: an example

5.1. Building the hierarchy model and its criteria

We first proposed over 30 criteria for R&D project selection based on reviewing relevant literature[2] and the current ITDP selection approach. We initially developed a hierarchy model of ITDP selection based on the criteria and then asked experts to review the hierarchy model for the sake of feasible application in ITDP selection. Eight experts from areas of technology management, materials engineering, electronics, and telecommunication were selected. We asked for an interview with the eight experts to review the initial ITDP hierarchy. By doing so, we could directly discuss with the experts and immediately revise the hierarchy model if it needed to be revised. A description brochure of criteria was also given to the eight experts to check whether these descriptions or definitions of criteria in the ITDP hierarchy were understandable. After revising both the hierarchy and descriptions of criteria, we finally developed a hierarchy ITDP selection model (see Fig. 2). Four aspects of the decision goal are as follows:

1. *Scientific and technological merit*: the technological impacts of ITDP project, including the competitiveness of technology and the relevance of technology.
2. *Potential benefits*: the excepted ITDP project benefits to the whole nation, including economic benefit and social benefit.
3. *Project execution*: the execution and implementation of ITDP project, including quality of technical plan and availability of resource.
4. *Project risk*: possible risk of ITDP project, including technical risk, development risk, and commercial risk.

Definitions of evaluating criteria of the ITDP selection are presented in Table 2.

5.2. Fuzzy weights of evaluation criteria

We interviewed 15 experts from the technical advisory committee to evaluate the ITDP hierarchy model. The aim of the interview was to understand the technical advisory committees' opinions in three aspects: (1) Their weight judgments of the ITDP decision criteria. (2) Their attitude toward the fuzzy AHP approach taken by this study. And (3) their suggestions to the ITDP policy in general.

These experts were asked to complete a questionnaire by pair-wise comparing the relative importance of criteria using a scale from 1 to 9. We analyzed their subjective judgments for the ITDP hierarchy model by ExpertChoice immediately. If the subjective judgments of the experts were inconsistent, we asked them to repeat the pair-wise comparison processes until the consistency index was less than 0.1. After these experts finished their assessments of relative importance for the ITDP model, we used the triangular membership function and α-cuts to convert the subjective judgments of the experts to become fuzzy judgments. Then, a degree of optimism for the experts was estimated by the index of optimism μ. That is, we first formulated all initial individual fuzzy comparison matrices based on triangular membership function and α-cuts in Excel and then used the geometric approach of Buckley [41] to integrate group fuzzy comparison matrices. Eq. (3) was used to transform fuzzy group comparison matrices into group

[2] [1–3,6,27,29,42–52].

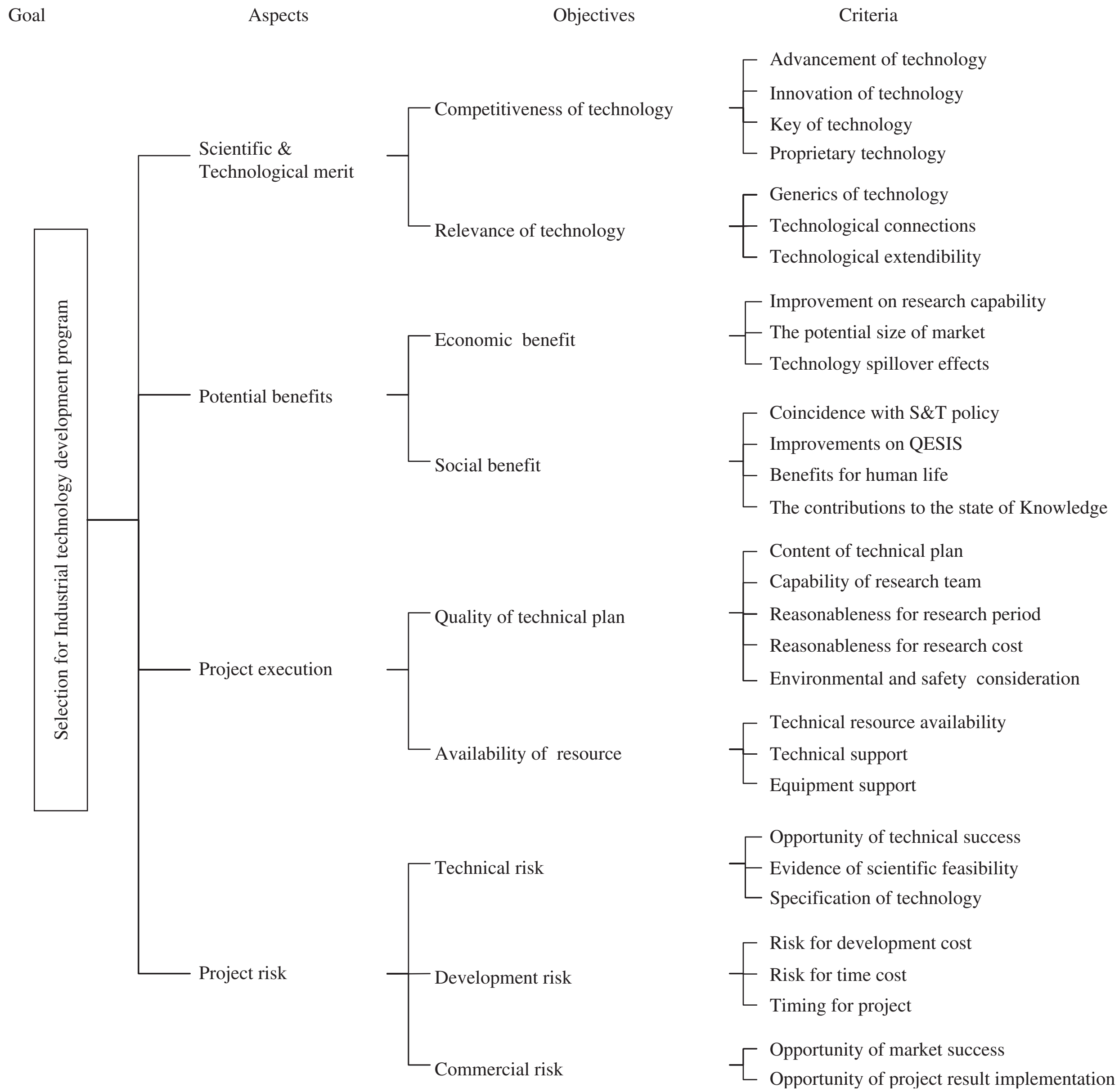

Fig. 2. The hierarchy model of ITDP selection.

crisp comparison matrices. Finally, we solved fuzzy eigenvalues and eigenvector at $\alpha=0.5$ and $\mu=0.5$ with a Matlab package. After combining the priorities over all hierarchy, overall importance weights of experts were determined. The fuzzy weights of the complete advisory committee are summarized in Tables 3, 4 and Fig. 3.

Generally, most aspects considered by the technical advisory committee reflect the ITDP to develop high technology R&D programs. As shown in Table 3, "scientific & technological merit (0.389)" is the most important factor in selecting ITDP projects, followed by "project execution (0.260)," "potential benefits (0.204)," and "project risk (0.147)." This finding is consistent with Hsu et al.'s [6] result that the value of R&D projects is most strongly determined by their scientific and technological aspects, whereas the aspects of project execution and potential benefits are important but relatively weaker. This can be explained because the aim of the ITDP is to develop advanced technology and the ITDP gets the most government funding so

Table 2
ITDP criteria

Criteria	Definition
Advancement of technology	How advanced is the proposed technology compared with existing technology
Innovation of technology	How innovative is the proposed technology
Key of technology	Is the proposed technology critical for product or industry development
Proprietary technology	Will the technology project generate a proprietary technology position through the intellectual property rights
Generics of technology	Is the proposed technology a generic technology to industry
Technological connections	The proposed technology is applicable for many products. The more technological applications, the higher technological connections
Technological extendibility	The extents to which proposed technology is potential for further technology development based on the project results
Improvements on research capability	The improvements on research human resource and research investments through proposed project
The potential size of market	The potential size/growth of market for products based on proposed technology
Technology spillover effects	The proposed technology shows positive effects on production for other firms
Coincidence with S&T policy	The extent to which proposed technology coincides science and technology policy
Improvements on QESIS	Benefits to society through the improvement in quality, environmental protection, industrial safety, national image and industrial standards
Benefits for human life	The proposed technology can result in benefits for human life such as quality of life and health
Contribution to knowledge	The extent to which proposed technology contributes to state of technical knowledge
Contents of technical plan	The project must be described questions including clear and concise planning, clear identification of the core technology, feasible technical approach and the major technical hurdles in substantial details
Capability of research team	The capability of research team such as the competence for project leader and involved technical staffs
Appropriateness for research period	The appropriateness of scheduling project period, permitting successful completion of the project objectives
Appropriateness for research cost	The appropriateness of scheduling project cost, permitting successful completion of the project objectives
Environmental and safety consideration	The extents to which proposed technology includes environment and public safety
Technical resource availability	The access to which project can obtain technical resources
Technical support	The extents to which project can be supported by organizational technology
Equipment support	The extents to which project can be supported by organizational facilities
Opportunity of technical success	How is opportunity of success for proposed technology and is there any similar successful technology
Evidence of scientific feasibility	Are there early research evidences such as a proof of concept, experimentation, or sound theoretical thinking for the proposed technology
Specification of technology	The specification risk results from whether project can meet the proposed specification.
Risk for development cost	The risk of expected total prototype development tangible monetary cost
Risk for time cost	The risk of expected total prototype development intangible time cost
Timing for project	Is it now the right timing to conduct the proposed project
Opportunity of market success	The opportunity of market success of product based on proposed technology
Opportunity of project result implementation	The opportunity of project result implementation based on financed company

Table 3
The fuzzy weight of aspects

Aspect	Weight	Ranking
Scientific and technological merit	0.389	❶
Potential benefits	0.204	❸
Project execution	0.260	❷
Project risk	0.147	❹

the advisory committee put more consideration on the technology aspects and execution aspects.

As noted in Table 4, the technical advisory committee put higher weights on competitiveness of technology (0.317), quality of the technical plan (0.170), economic benefit (0.154) and the availability of resources (0.090). One ITDP strategy is to press for the internationalization of industrial technology R&D to upgrade Taiwan's technology R&D competitiveness [46], compared with other countries. Thus, the competitiveness

Table 4
The fuzzy weight of objectives

Objective	Weight	Ranking
Competitiveness of technology	0.317	1
Relevance of technology	0.072	5
Economic benefit	0.154	3
Social benefit	0.050	7
Quality of technical plan	0.170	2
Availability of resource	0.090	4
Technical risk	0.064	6
Development risk	0.038	9
Commercial risk	0.045	8

of the technology is the most important consideration of the committee.

According to the DOIT [46], there were 588 projects submitted for evaluation from 1991 to 2004. Due to the great number of projects, experts in the technical advisory committee find it hard to review projects, so they put higher weight on the quality of technical proposals. In addition, experts in the technical advisory committee also emphasize the economic benefits more than the social benefits. This result is the same as those of Hsu et al. [6] and ATP [3]. In general, technology R&D programs will not only result in commercial benefits for subsidized companies but should also extend economic benefits to country. The fact that Taiwanese industries often need to purchase technical resources or equipment from other countries might be the reason why the

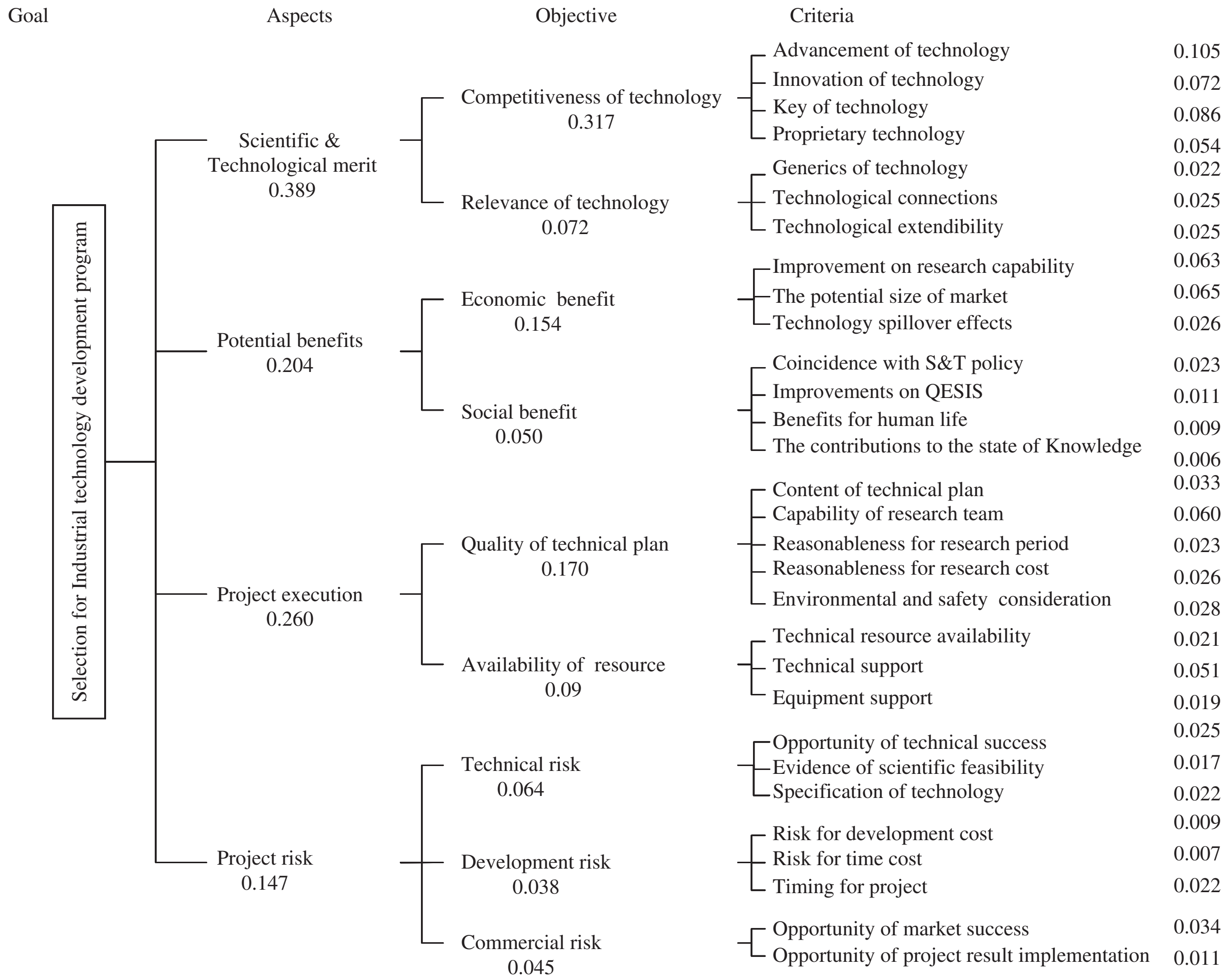

Fig. 3. The weights of ITDP hierarchy model.

experts emphasize the availability of resources. This result also reflects the situation of limited resources in Taiwan.

In Fig. 3, the advancement of technology (0.105) gets the highest weight, followed by key of technology (0.086), innovation of technology (0.072), the potential size of the market (0.065), improvements to research capability (0.063), the capability of research team (0.060), proprietary technology (0.054), technical support (0.051), opportunity of market success (0.034), and contents of technical plan (0.033). This reflects the objectives and responsibilities of the technology development program in Taiwan, including: (1) Develop key technologies and components to speed up the upgrading of traditional industries. (2) Develop innovative technologies to assist in setting up new industries and leading industries. And (3) develop advanced technologies to be more superior to domestic industrial technologies in Taiwan [46]. That is, technology inherence is more important to a competitive technology market.

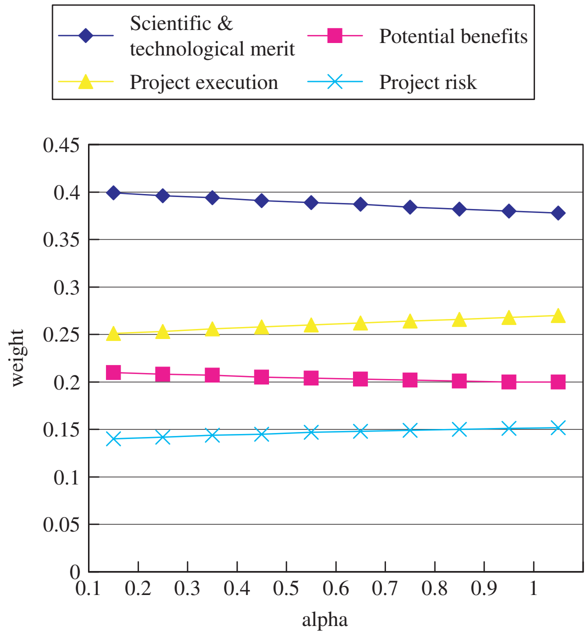

Fig. 4. Simulation of aspects.

6. Incorporating with decision-makers' degree of optimism

The degree of optimism of decision-makers may have significant influence on decision-making. Our fuzzy AHP model can analyze variation of weights of decision criteria by combining both the index of optimism μ and the interval of confidence α in fuzzy AHP. By incorporating α value with μ value, our model can simulate changes of criteria weighting of the technical advisory committee in ITDP selection. We set α value from 0.1 to 1,[3] but fix μ value at 0.5 to reflect moderate optimism of ITDP experts. The simulation results are shown in Figs. 4–8.

Fig. 4 shows the weights of the scientific & technological merit, potential benefit, project execution, and project risk aspects, as a function of α. It is found that the weights for the first two aspects (i.e., scientific & technological merit and potential benefit) decrease, but those for the last two aspects (i.e., project execution and project risk) increase, as α increases from 0.1 to 1. This result shows that when decision risk gets lower, the experts reduce the relative importance on the first two aspects but enhance the relative importance on the last two aspects. Most importantly, no matter how α changes, the scientific & technological merit and project execution are always considered to be the most important two aspects by the ITDP experts. In other words, the potential benefit and project risk are always considered less important, compared with the scientific & technological merit and project execution.

Fig. 5 shows the weights of competitiveness of technology, relevance of technology, economic benefits, social benefits, quality of the technical plan, availability of resources, technical risks, development risks, and commercial risks, as a function of α. It is found that the weights for the first four aspects (i.e., competitiveness of technology, relevance of technology, economic benefit and social benefit) decrease, but those for the last five aspects (i.e., quality of technical plan, availability of resource, technical risk, development risk and commercial risk) increase, as α increases from 0.1 to 1. This result shows that when decision risk becomes lower, the experts reduce the relative importance on the first four aspects but enhance the relative importance on the last five aspects. Most importantly, no matter how α changes, the criteria ranking is the same as that of Table 4.

The results of Figs. 6–8 can be classified into three kinds of judgment: (1) The weights of criteria decrease when α value changes from 0.1 to 1. (2) The weights of criteria increase when α value changes from 0.1 to 1. And (3) the weights of criteria do not change no matter how α value changes.

Judgment 1: The criteria are assessed with lower weights when α value changes from 0.1 to 1. These criteria include advancement of technology (weight

[3] Experts encounter higher uncertainty in ITDP selection if α value is lower.

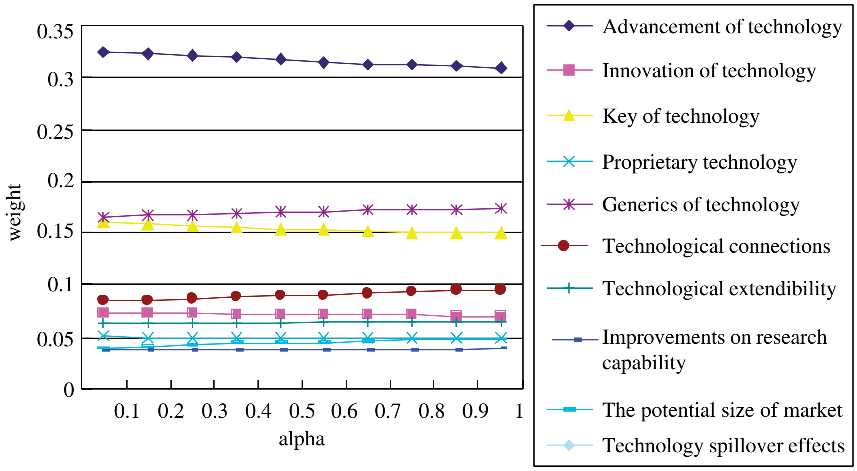

Fig. 5. Simulation of objectives.

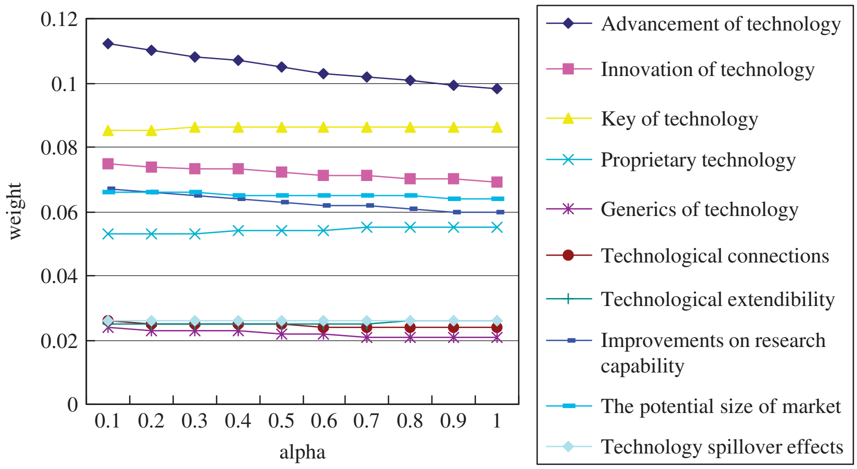

Fig. 6. Simulation of criteria.

changed from 0.112 to 0.098), innovation of technology (weight changed from 0.075 to 0.069), generics of technology (weight changed from 0.024 to 0.021), technological connections (weight changed from 0.026 to 0.024), improvements on research capability (weight changed from 0.067 to 0.060), the potential size of the market (weight changed from 0.066 to 0.064), coincidence with S&T policy (weight changed from 0.024 to 0.022), contents of technical plan (weight changed from 0.034 to 0.031), opportunity of technical success (weight changed from 0.026 to 0.025), improvements on QESIS (weight changed from 0.012 to 0.011), and risk of development costs (weight changed from 0.009 to 0.008). This reveals ITDP experts put lower considerations on the 11 criteria when the industrial development environment is steadier. It is worth mentioning that advancement of technology and innovation of technology get the biggest decrease when α value changes from 0.1 to 1. In general, the development of advanced or innovative technology could easily fail in a risky environment so ITDP experts emphasize the two criteria. However, ITDP experts may not put more consideration on the two criteria when a company can proceed technology R&D activities easily due to a steady environment.

Judgment 2: The criteria are assessed with higher weights when α value changes from 0.1 to 1. These criteria include key of technology (weight changed from 0.085 to 0.086), technological extendibility (weight changed from 0.025 to 0.026), proprietary technology

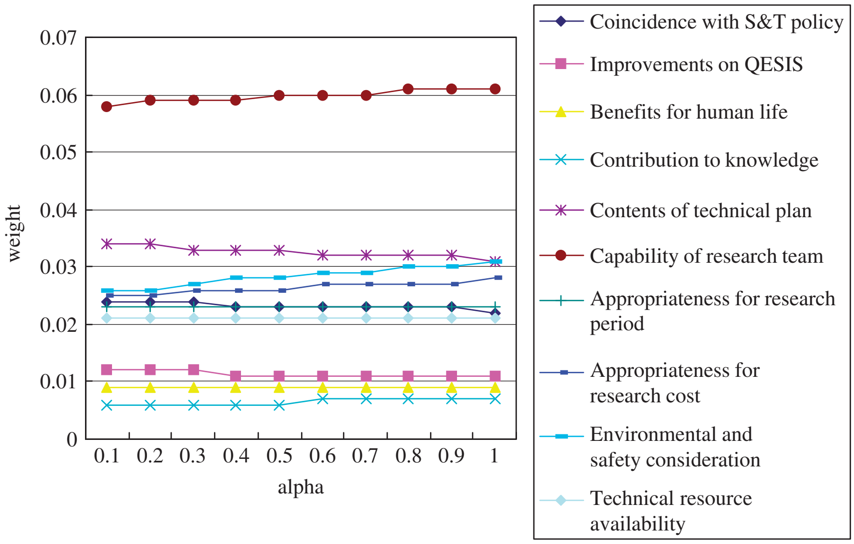

Fig. 7. Simulation of criteria.

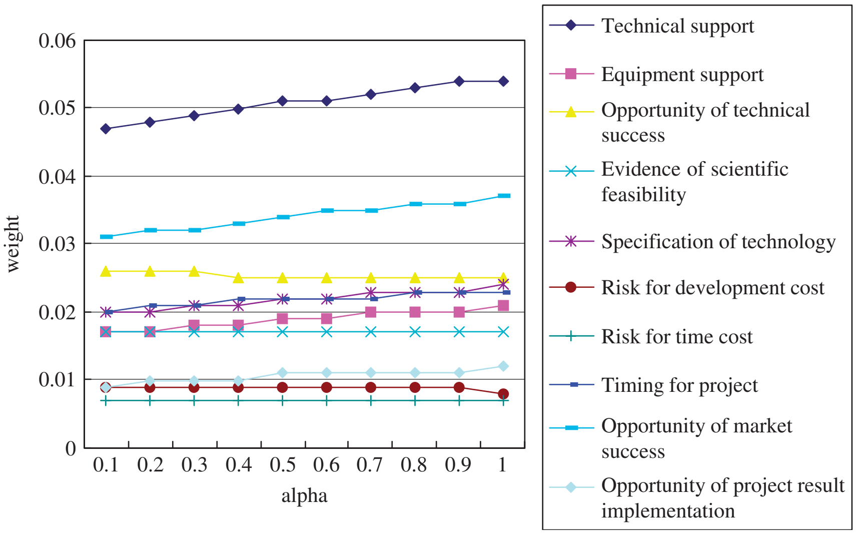

Fig. 8. Simulation of criteria.

(weight changed from 0.053 to 0.055), capability of the research team (weight changed from 0.058 to 0.061), appropriateness for research cost (weight changed from 0.025 to 0.028), environmental and safety considerations (weight changed from 0.026 to 0.031), technical support (weight changed from 0.047 to 0.054), equipment support (weight changed from 0.017 to 0.021), specification of technology (weight changed from 0.020 to 0.024), timing for project (weight changed from 0.020 to 0.023), opportunity of market success (weight changed from 0.031 to 0.037), opportunity of project result implementation (weight changed from 0.009 to 0.012), and contribution to knowledge (weight changed from 0.006 to 0.007). That means ITDP experts put more considerations on the 13 criteria when uncertainty is low. Among the criteria, the opportunity of project implementation gets the highest increase when α value changes from 0.1 to 1. In a steady industrial development process, successful implementation of R&D projects is regarded as very important for a company.

Judgment 3: The weights of criteria do not change when α value changes from 0.1 to 1. These criteria include technology spillover effects (weight fixed at 0.026), appropriateness for research period (weight fixed at 0.023), technical resource availability (weight fixed at 0.021), evidence of scientific feasibility (weight fixed at 0.017), benefits for human life (weight fixed at 0.009) and risk of time cost (weight fixed at 0.007). Based on above results, the ITDP experts do not change their judgments, no matter how the decision risk changes.

7. Important implications of the interview of ITDP technical advisory committee

7.1. Establishing structural evaluation criteria is the basis for selecting technology R&D projects

In Taiwan, the DOIT developed evaluation criteria for ITDP selection. The ITDP experts directly score the projects on these criteria without any weighting. However, the criteria weighting may have significant influences on ITDP experts' judgments. The interviewed experts said the ITDP hierarchy structure in our study is systematic. The hierarchy can help them to evaluate submitted ITDP projects. Besides, all the interviewed experts indicated that the criteria in the ITDP hierarchy structure are sufficient to evaluate ITDP projects. The interviewed experts said the weights of criteria in our study also reflect their subjective judgments and are useful for their evaluations on ITDP projects more objectively and fairly than before. All of them expressed the view that our study is highly feasible and urged us to present our research results in the forthcoming ITDP annual meeting.

7.2. The need of experts from industry

Most the interviewed experts said the DOIT should increase the number of experts who have sufficient experience in scientific and technological (S&T) development. That is, experts can understand whether submitted projects can be implemented if experts are familiar with the industrial S&T development. In addition, the interviewed experts said that they had to undertake a heavy review workload to complete the review process. The DOIT may need to increase the number of available new experts to reduce the workload of current experts.

7.3. The ITDP budget allocation

Current ITDP budget allocation follows a "first come first serve" rule. However, ITDP budgets are ended quickly so newly submitted projects cannot get any funding even though these new projects can develop advanced or innovative technology. Most of the interviewed experts expressed that the DOIT needs to provide more budgets and develop a flexible budget plan to sponsor more ITDP projects.

7.4. The suggestions for potential ITDP applicants

The interviewed experts indicated that ITDP project applicants should perform surveys for market size and technology competitiveness to check whether submitted projects are worthy of being developed. This reflects the competitiveness of technology being the most important evaluation criteria as indicated in Table 4. The potential size of market is also one major consideration. As shown in Fig. 3, proprietary technology is one of the important evaluation criteria. The interviewed experts also suggested that ITDP project applicants carry out surveys for intelligence property and patent. In doing so, ITDP project applicants can avoid legal problems, particularly in relation to the law of torts. Moreover, the interviewed experts suggested that the DOIT no longer accepts project applications from the firms that sponsored by government previously but failed in developing new technology several times.

8. Conclusions

Many studies used the AHP to select R&D projects in the private sector; however, the selection process of government-sponsored R&D projects is discussed less. In this study we used a fuzzy Analytic Hierarchy Process (fuzzy AHP) in government-sponsored R&D projects. We employed a simulation to understand changes in the judgments of the technical advisory committee when they considered different decision risks. We also interviewed experts to understand ITDP policy implications and whether the fuzzy AHP approach is feasible for selecting government-sponsored R&D projects. Thus, the contribution of this study is to extend the fuzzy AHP application for R&D project selection in the public sector.

Additionally, current fuzzy AHP studies in public R&D projects like Hsu et al. [6] and Wang et al. [13] do not consider decision risk. We integrated the degree of optimism to simulate expert judgments in different decision risks.

Evaluating government-sponsored R&D projects usually requires specialized knowledge as well as experience and experts may display subjectivity judgments. Current ITDP selection methods in Taiwan may not fairly solve disparity. The fuzzy AHP approach proposed in this study shows some advantages: (1) AHP helps decision-makers to decompose decision problems for forming hierarchical decision structure. (2) The fuzzy approach helps to formulate judgment vagueness for government-sponsored R&D project selection. (3) The simulation process helps to understand how expert judgments change in different decision risks by incorporating the degree of optimism. And (4) the fuzzy AHP helps to resolve disparity among experts.

Although the fuzzy AHP approach in this study is suitable for ITDP selection, there are some limitations. First, evaluation criteria in this study are considered independent. It is clear that additional model refinement is required to better understand the correlations among criteria. An alternative model with "crossover" effects among these evaluation criteria, i.e., analytic network process [53] is suggested. Second, although we made efforts to solicit official information of the approved ITDP projects to validate our research results, we were still unable to access the official information because of the administrative concern of confidentiality. Further studies incorporating the information of the approved ITDP projects are necessary to assess the precise level of generalization these research results and to evaluate the full impact on people working in the same field.

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