Using the fuzzy analytic network process for selecting technology R&D projects

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Abstract: Technology development programs have proven to be useful strategies for governments to encourage private firms to undertake R&D projects. Due to limited budgets, a government must select proper R&D projects for funding. R&D project selection is full of uncertainty and can be viewed as a multiple-criteria decision that is normally made by a review committee. In this study, we propose a fuzzy analytic network process method to handle interdependency among evaluation criteria and integrate the divergent judgements of experts in a R&D project selection committee. Our findings suggest that 'scientific and technological merit' and 'project execution' are the most important criteria and, moreover, indicate that the relative importance of evaluation criteria changes in different degrees of uncertainty.

Keywords: technology R&D projects; fuzzy analytic network process.

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1 Introduction

In many countries, technology development programs (TDP) have proven to be useful strategies for governments to encourage private firms to undertake R&D projects (Sakakibara, 1997). For example, the US initiated the advanced technology program (ATP) in 1990 to encourage industries to develop technology projects. The ATP has approved 768 R&D projects and committed a total of US$2,269 million between 1990 and 2004 (ATP, 2006). The European Union and some Organisation for Economic Cooperation and Development countries, such as the UK, Japan and China, have all launched ATPs to encourage private firms to develop core technologies. Taiwan launched similar government-sponsored TDPs in 1997, including the Industrial Technology Development Program (ITDP) and the Small Business Innovation Program (SBIR). Since then, actual expenditures on TDPs have increased from NT$15.17 billion to NT$18.22 billion from 2001 to 2005. With respect to the benefits of research and development, Taiwanese TDP initiatives have produced 618 firm investments and a total of NT$10.5 billion in benefits has been generated from technology transfers and patents (DoIT, 2006a).

Despite the fact that the economic literature has provided rationales for the public subsidisation of the private sector (Baron, 1998; Lerner, 1999; Audretsch et al., 2002; Salmenkaita and Salo, 2002), it remains imperative for policy makers to develop ways to select appropriate government-sponsored R&D projects. However, decisions to determine proper R&D projects at a national level are difficult, particularly when candidate projects come from multiple fields and disciplines (Wang et al., 2005). Hsu et al. (2003) and Kutlaca (1997) noted that government-supported R&D projects differ from those of the private sector in four aspects:

1. Government-supported R&D is a strategic, long-term investment. Thus, conventional financial 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 R&D projects is increased due to the ambiguity of innovative technology and the lack of experts.
4. Finally, R&D requires technical expertise and is influenced by government policies.

Due to the large funding scale and complex evaluation criteria, the selection of TDP projects can be viewed as a multiple-criteria decision that is normally made by a review committee with experts from academia, industry and the government. Analytic hierarchy process (AHP) (Saaty, 1980), an intuitive and easily-used decision method, is one of the most popular and powerful methods for group decision-making in project selection (Liberatore, 1987; Brenner, 1994; Al-Harbi, 2001). However, decisions involving linguistic or vague descriptions cannot be solved easily using AHP. Moreover, R&D portfolio decisions deal with future events and opportunities, and much of the information required to make portfolio decisions is at best uncertain and at worst very unreliable (Wang and Hwang, 2007). In such uncertain situations, decision makers may not be able or may be reluctant, to provide exact judgements (Mikhailov, 2004).

A natural way to cope with uncertain cases is to represent uncertain judgements using fuzzy set theory. First proposed by Zadeh (1965), fuzzy set theory offers a more natural way of dealing with ambiguities involved in data evaluation processes (van Laarhoven and Pedrycz, 1983; Buckley, 1985; Gogus and Boucher, 1997; Sengupta and Pal, 2000). Fuzzy set theory has extended traditional mathematical decision theories in order to cope well with uncertain problems that cannot adequately be treated using probability distributions (Hwang and Yu, 1998; Deng, 1999; Chen, 2001). Coffin and Taylor (1996) first presented multiple-criteria R&D project selection using fuzzy logic. Chan et al. (2000), Hsu et al. (2003), Huang et al. (2008) and Wang et al. (2005) also proposed project selection models based on fuzzy multiple-criteria methods.

We have previously proposed a fuzzy hierarchical model to analyse TDP project selection in Taiwan[1]. Although the fuzzy hierarchical approach may help resolve linguistic or uncertain problems, many TDP experts involved in developing the fuzzy hierarchy model have noted that dependence effects may exist among evaluation criteria; they have suggested that improvements in the hierarchical model for TDP decision-making processes may be very helpful. Their suggestion is consistent with literature that maintains that decision makers might have to accept strong abstraction and homogenisation of a complex problem due to its hierarchical structure (Wolfslehner et al., 2005) and, moreover, that most decisions must be free from assumptions of independence to fully account for the complex problems in which they arise (Saaty and Takizawa, 1986).

Analytic network process (ANP) (Saaty, 1996) is a multi-criteria decision-making approach that allows decision makers to consider qualitative and quantitative evaluation criteria and the complex interrelationships among them. It has been presented for use in project selection (Lee and Kim, 2000, 2001). By incorporating fuzzy set theory with ANP, a fuzzy version of ANP (i.e., fuzzy ANP) allows a more accurate description of the decision-making process. Mikhailov and Singh (2003) first proposed fuzzy ANP for the development of decision support systems. Mohanty et al. (2005) applied fuzzy ANP to R&D project selection in the private sector. A few studies (Tian et al., 2003; Büyüközkan et al., 2004) further applied it to design requirements for quality and supply chain management. However, there is no existing research applying fuzzy ANP to R&D project selection in the public sector.

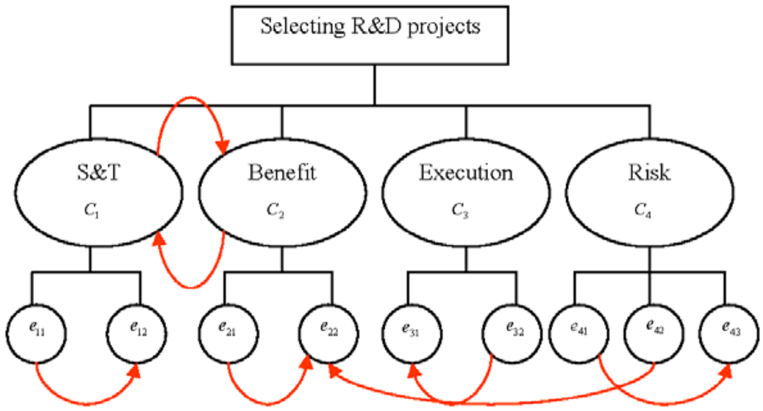
In this study, we propose a fuzzy ANP model for technology project selection in the public sector. We then analyse ITDP review committee judgements in the context of various technological areas and degrees of uncertainty. In conclusion, we discuss limitations and policy implications of TDP project selection in the public sector.

2 Fuzzy ANP

2.1 Essences of ANP

In ANP, interdependencies may be graphically represented by two-way arrows (or arcs) between decision levels or, if within the same decision level of analysis, a looped arc. The directions of the arcs signify dependence. Arcs emanate from one criterion to another criterion that may influence it. There are two kinds of dependence in ANP, i.e., inner dependence and outer dependence. As shown in Figure 1, loops in criteria C_1, C_2, C_3 and C_4 represent inner dependence of the elements (i.e., e_{11} has an influence on e_{12}) in that criterion with respect to a common property. Outer dependence is the dependence between criteria. As noted in Figure 1, the arc from risk C_4 to benefit C_2 show the outer dependence of the elements in C_2on the elements in C_4 (i.e., e_{42} has an influence on e_{22}). There is a feedback effect between scientific and technology (S&T) merit $C_1$and benefit C_2.

Figure 1 The interdependency among criteria in ANP structure (see online version for colours)



The ANP approach addresses interdependence among elements by obtaining composite weights through the development of a 'super matrix'. Raising the super matrix to the power $2k + 1$, the interdependent relationships converge and the overall priorities in ANP are generated. Figure 2 represents the ANP structure for R&D project selection that has criteria with inner dependence but no outer dependence apart from the ultimate goal for selection. w_1 is a matrix that represents the impact of the goal on each of the first-tier criteria; w_2 is a matrix that shows the impact of the first-tier criteria on each of the second-tier criteria; w_3 is a matrix that denotes the impact of the second-tier criteria on each of the third-tier criteria and w_4 is a matrix that represents the inner dependence among the second-tier criteria. The super matrix of Figure 2 is shown in Figure 3.

Figure 2 Network representation of R&D project selection model

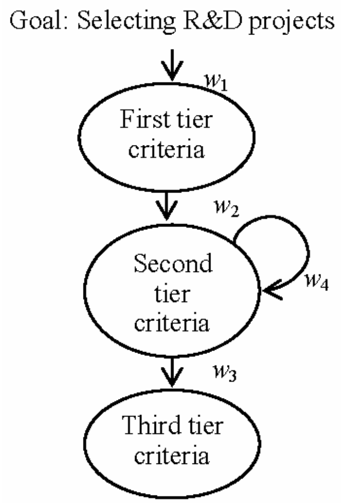


Figure 3 Super matrix of Figure 2

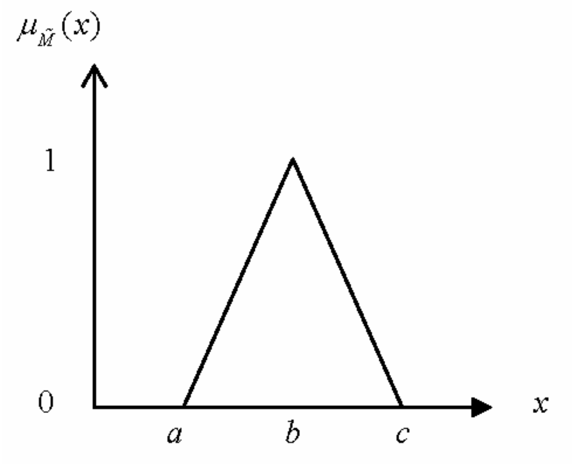
$$W = \begin{array}{r} \\ \text{Goal}(G) \\ \text{Criteria}(C_1) \\ \text{Criteria}(C_2) \\ \text{Criteria}(C_3) \end{array} \begin{array}{c} \begin{matrix} G & C_1 & C_2 & C_3 \end{matrix} \\ \begin{pmatrix} 0 & 0 & 0 & 0 \\ w_1 & 0 & 0 & 0 \\ 0 & w_2 & w_4 & 0 \\ 0 & 0 & w_3 & 0 \end{pmatrix} \end{array}$$

2.2 Fuzzy set theory

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 fuzzy criterion judgement. A triangular fuzzy number (TFN) is denoted as $\tilde{M} = (a,b,c)$, where $a \leq b \leq c$ and has the triangular membership function shown in both equation (1) and Figure 4.

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

Figure 4 Triangular membership function



By defining the interval of confidence level α, the TFN can be described as in equation (2):

$$\begin{aligned} &\forall \alpha \in [0,1] \\ &\tilde{M}_\alpha = [a^\alpha, c^\alpha] = [(b-a)\alpha + a, -(c-b)\alpha + c] \end{aligned} \tag{2}$$

Lower values of α represent higher uncertainty and higher values of α represent lower uncertainty. By 'fuzziness', we mean the lengths of the α-cuts. Using α-cuts, we can convert the interval subjective judgements of experts into fuzzy judgements under different degrees of uncertainty. TFNs, ranging from $\tilde{1}$ to $\tilde{9}$, are used to represent subjective pair-wise comparisons in order to capture vagueness. The fuzzy judgement matrix is constructed through a pair-wise comparison of TFNs.

2.3 Computational procedure of fuzzy ANP

Based on Saaty and Takizawa (1986), the computational procedure corresponding to our fuzzy ANP model is as follows. A simplified example is presented in Appendix A.

Step 1 Scaling the relative strength of the criteria and alternatives

Since a triangular function is the easiest and the simplest way to express the fuzzy set (Pedrycz, 1994), we employ TFNs ($\tilde{1}$ to $\tilde{9}$) to indicate the relative strength of each criterion and alternative.

Step 2 Computing the fuzzy judgement matrix

Assume that there are K criteria C_1, C_2,… C_K with a corresponding fuzzy judgement matrix $\tilde{A}_k$ for each C_k, $1 \leq k \leq K$. A decision maker supplies pair-wise comparisons of all criteria to produce a fuzzy judgement matrix $\tilde{E}$. The fuzzy judgement matrices $\tilde{A}_k\left(\tilde{a}_{ij}\right)$ and $\tilde{E}\left(\tilde{e}_{ij}\right)$ are computed by utilising TFNs 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 $i = j$, $a_{ij} = 1$, such that $i \neq j$, $a_{ij} = \tilde{1} \sim \tilde{9}, \tilde{9}^{-1} \sim \tilde{1}^{-1}$.

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

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

Step 3 Solving fuzzy eigenvalues

A fuzzy eigenvalue λ is a fuzzy number solution to equation (3).

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x}, \tag{3}$$

where $\tilde{A}$ is an nxn fuzzy matrix containing fuzzy number $\tilde{a}_{ij}$ and $\tilde{x}$ is a non-zero $nx1$ fuzzy eigenvector containing the fuzzy number $\tilde{x}_i$. Fuzzy multiplication and addition are performed by using interval arithmetic and α-cuts. Equation (3) is equivalent to equation (4).

$$\left[a^{\alpha}{}_{i1l}x_{1l}{}^{\alpha}, a^{\alpha}{}_{i1u}x_{1u}{}^{\alpha}\right] \oplus \cdots \oplus \left[a^{\alpha}{}_{inl}x_{nl}{}^{\alpha}, a^{\alpha}{}_{inu}x_{nu}{}^{a}\right] = \left[\lambda x_{il}{}^{\alpha}, \lambda x_{iu}{}^{\alpha}\right], \tag{4}$$

where

$$\begin{aligned} &\tilde{A} = \left[\tilde{a}_{ij}\right], \tilde{x} = \left(\tilde{x}_1, ..., \tilde{x}_n\right), \\ &a^{\alpha}{}_{ij} = \left[a^{\alpha}{}_{ijl}, a^{\alpha}{}_{iju}\right], \tilde{x}_j = \left[x_{il}{}^{\alpha}, x_{iu}{}^{\alpha}\right], \lambda_l^{\alpha} = \left[\lambda_l{}^{\alpha}, \lambda_u{}^{\alpha}\right] \end{aligned} \tag{5}$$

for $0 < \alpha \leq 1$ and all i, j, where $i = 1, 2, \ldots, n, j = 1, 2\ldots, m$.

Step 4 Determining the weights for criteria and alternatives

Compute the fuzzy weights $\tilde{w}_k = \left(\tilde{w}_{1k,\ldots,}\tilde{w}_{nk}\right)$ for $\tilde{A}_k$, i.e., $\tilde{w}_{1k} = \left(w_{\alpha_1 1l}, w_{1m}, w_{\alpha_1 1u}\right)$ and fuzzy weights $\tilde{e} = \left(\tilde{e}_{1,\ldots,}\tilde{e}_K\right)$ for $\tilde{E}$, i.e., $\tilde{e}_1 = \left(e_{\alpha_1 1l}, e_{1m}, e_{\alpha_1 1u}\right)$.

Step 5 Estimating the fuzzy weight w_{α}^{*} based on constant $K_{\alpha l}$ and $K_{\alpha\mu}$

Csutora and Buckley (2001) proposed the $\lambda_{\max}$ method to find the fuzzy weights in a fuzzy hierarchical analysis, which is the direct fuzzification of the $\lambda_{\max}$ method used by Saaty (1980) in AHP. They chose $K_{\alpha l}$ and $K_{\alpha\mu}$ in order to minimise the fuzziness of the $\tilde{w}_{\alpha}{}^{*}\left(w^{*}{}_{\alpha il}, w^{*}{}_{\alpha i\mu}\right)$. By the 'fuzziness', we mean the lengths of α-cuts. We minimise the fuzziness so that we can 'spread out' the alternatives for the final ranking. That is, choose α_i in [0, 1] so that $0 = \alpha_n < \alpha_{n-1} < \ldots < \alpha_1 < 1$. We first find $w_{\alpha 1il}^{*}$ and $w_{\alpha 1i\mu}^{*}$, $1 \leq i \leq n$ and then determine $\left(w_{\alpha 2il}^{*}, w_{\alpha 2i\mu}^{*}\right), 1 \leq i \leq n.$ We work our way down to finally obtain $\left(w_{0il}^{*}, w_{0i\mu}^{*}\right), 1 \leq i \leq n.$ Here, we illustrate for α_1 and α_2. Define:

$$\begin{aligned} K_{\alpha_1 l} &= \min\left\{\frac{w_{im}}{w_{\alpha_1 il}} | 1 \leq i \leq n\right\} \\ K_{\alpha_1 u} &= \max\left\{\frac{w_{im}}{w_{\alpha_1 iu}} | 1 \leq i \leq n\right\}, \end{aligned} \tag{6}$$

Then $w_{\alpha 1il}^{*} \leq w_{im} \leq w_{\alpha 1i\mu}^{*}$, for all i.

According to equation (7), in order to obtain the revised fuzzy weights $\tilde{w}_k^{*} = \left(\tilde{w}_{1k,\ldots,}^{*}\tilde{w}_{nk}^{*}\right)$ and $\tilde{e}^{*} = \left(\tilde{e}_{1,\ldots,}^{*}\tilde{e}_K^{*}\right)$, we combine $\tilde{w}_k = \left(\tilde{w}_{1k,\ldots,}\tilde{w}_{nk}\right)$ for $\tilde{A}_k$, i.e., $\tilde{w}_{1k} = \left(w_{\alpha_1 1l}, w_{1m}, w_{\alpha_1 1u}\right)$ with constant $K_{\alpha l}$ and $K_{\alpha\mu}$, and we combine $\tilde{e} = \left(\tilde{e}_{1,\ldots,}\tilde{e}_K\right)$ for $\tilde{E}$, i.e., $\tilde{e}_1 = \left(e_{\alpha_1 1l}, e_{1m}, e_{\alpha_1 1u}\right)$ with constant $K_{\alpha l}$ and $K_{\alpha\mu}$.

$$\begin{aligned} w_{\alpha l}^{*} &= K_{\alpha l} w_{\alpha l} \\ w_{\alpha u}^{*} &= K_{\alpha u} w_{\alpha u} \end{aligned} \tag{7}$$

We define

$$K_{\alpha_2 l} = \min\left\{ \frac{w^*_{\alpha_1 il}}{w_{\alpha_2 il}} | 1 \le i \le n \right\}$$
$$K_{\alpha_2 u} = \max\left\{ \frac{w^*_{\alpha_1 iu}}{w_{\alpha_2 iu}} | 1 \le i \le n \right\}. \tag{8}$$

We obtain $0 < w^*_{\alpha_2 il} \le w^*_{\alpha_1 il} \le w_{1m} \le w^*_{\alpha_1 i\mu} \le w^*_{\alpha_2 i\mu}$, for all i. In fact, we iterate the process until we generate all revised fuzzy weights under possible α-cuts, i.e., $0 = \alpha_n < \alpha_{n-1} < \ldots < \alpha_1 < 1$.

Step 6 Determining the interdependent weights w_α^{inter}

We ask experts 'what has a greater influence and how much more?' to develop criteria interrelationships in order to estimate the inner dependence matrix W_α^{inner}, which consists of priority vectors of elements with inner dependence. The priority vectors of dependent elements are then calculated using Step 1 to Step 5. Subsequently, the value of w_α^{inter} is determined by $w_\alpha^{\text{inter}} = W_\alpha^{inner} \times w_\alpha^*$.

Step 7 Pooling the weights from various experts

Fuzzy ANP allows us to rank alternatives across all criteria. After synthesising all priorities in a network, the final fuzzy weights for alternative A_j are determined by varying the value of α. The final alternatives are given by the vector $r^T = \left(r_1^*, \ldots r_n^*\right)$, where $r_j^* = \sum_{k=1}^{K} w_{jk}^* e_k^*$. We pool the weights from the various experts using equation (9).

$$r = \left(\frac{1}{n}\right) \otimes \left(r_1^* \oplus r_2^*, \ldots \oplus r_n^*\right). \tag{9}$$

3 Applications and contribution of fuzzy ANP

3.1 Interdependence in fuzzy MCDM

Decision-making with interdependent multiple criteria is a surprisingly difficult task (Carlsson and Fuller, 1996). Many studies have proposed modified methods or processes for MCDM to solve interdependence among evaluation criteria. Saaty and Vargas (1998) proposed a modified AHP framework to deal with dependence among the elements and/or the clusters of a decision structure when combining statistical and judgemental information. They showed that the posterior probabilities derived from the Bayes theorem are part of this framework and hence, the Bayes theorem is a sufficient condition for an AHP solution. Many studies have integrated the concept of ANP into decision-making. Lee and Kim (2001) suggested an integrated approach for selecting interdependent information system projects using Delphi, ANP concept and zero-one goal programming. Meade and Presley (2002) first used ANP in R&D project selection in the private sector. Shyur and Shih (2006) proposed a hybrid model for supporting vendor selection processes in new task-oriented situations. They integrated ANP and a modified technique for order performance by similarity to idea solution (TOPSIS) in a five-step hybrid process that ultimately ranked competing products in terms of their overall performance. Even though we can divide a complex system into subsystems, which can then be more easily evaluated, the relative weights of the subsystems are also a crucial problem (Huang et al., 2005). Because interdependence and feedback usually exist between these subsystems, their weights are difficult to calculate. Thus, Huang et al. (2005) proposed a method that combines methods of interpretive structural modelling and ANP to address interdependence and feedback in subsystems.

Research on multiple criteria analysis under uncertainty has also been emphasised in relation to interdependence between criteria. Generalising the principle of application functions to fuzzy multiple objective programs with interdependent objectives, Carlsson and Fuller (1994) defined a large family of application functions for fuzzy multiple objective programs and illustrated their ideas by a simple program with three objectives. Also, Carlsson and Fuller (1995) demonstrated that the use of interdependence among objectives in multiple-objective linear programming in the definition of application functions increases the number of correct solutions and the speed of convergence. Yu and Tzeng (2006) proposed fuzzy decision maps, which incorporate the eigenvalue method, fuzzy cognitive maps and the weighting equation to overcome the problem of preferential independence. Felix (1992) presented a novel theory for multiple-attribute decision-making based on fuzzy relations between objectives in which the interactive structure of objectives is inferred and represented explicitly. Moreover, fuzzy ANP has been applied to real-world decision problems. Mikhailov and Singh (2003) first proposed the application of fuzzy ANP to the development of decision support systems. Mohanty et al. (2005) used fuzzy ANP to model R&D project selection in the private sector. However, applications of fuzzy ANP to government-supported project selection are relatively sparse.

3.2 The contribution of fuzzy ANP to R&D project selection

Meade and Presley (2002) indicated that even with the large number of proposed models, R&D selection remains problematic and few models have gained wide acceptance. Many R&D project selection models and techniques, including qualitative and quantitative approaches, have appeared in the literature (Baker and Freeland, 1975; Souder and Mandakovic, 1986; Hall and Nauda, 1988; Oral et al., 1991; Henriksen and Traynor, 1999; Ernst and Soll, 2003; Hänninen, 2007). These selection models may be classified into mathematical models (i.e., linear programming or goal programming), financial models (i.e., net present value or cost-benefit analysis) and decision theory models (i.e., multi-criteria decision-making or decision trees). Liberatore and Titus (1983) indicated that mathematical models such as linear and integer programming methods are not commonly used in the selection of R&D projects because of the diversity of project types, resources and criteria. Besides, mathematical models are complex for managers to use (Hall and Nauda, 1988; Coldrick et al., 2002). Liberatore and Titus (1983) also found that most firms use one or more traditional financial approaches to estimate project returns. Although financial models utilise tangible or monetary components to evaluate R&D projects, the criteria of R&D projects may include non-monetary criteria that are difficult to quantify. Furthermore, expert judgements may be necessary for selecting proper R&D projects. Financial models and mathematical models cannot handle the subjective judgements of experts. Therefore, decision theory models, specifically fuzzy ANP, may be more suitable for modelling government-supported project selection.

Fuzzy ANP is a novel decision theory approach to R&D project selection. ANP can account for interdependence among criteria and alternatives in project selection process. In addition, ANP can measure tangible and intangible criteria (Lee and Kim, 2000; Saaty, 2004). ANP is a relatively simple, intuitive approach that can be relatively easily adopted by managers and other decision makers (Meade and Presley, 2002). Fuzzy ANP includes these characteristics of ANP but can also handle the uncertainty problem in R&D project selection. As illustrated by Table 1, fuzzy ANP is better than other project selection models.

Table 1 Comparisons of R&D project selection models

Perspectives	*Mathematical models*	*Financial models*	*Decision theory models*	*Fuzzy ANP*
Consideration of uncertainty	✓	✓	✓	✓
Incorporation of monetary or non-monetary aspects	✓	✓	✓	✓
Treatment of interrelationships among criteria/projects	×	×	×	✓
Consideration of judgements of different stakeholders	×	×	✓	✓
Perceptions by managers that models are easy to understand and use	×	✓	✓	✓

4 The ITDP project selection model

4.1 R&D selection models

Typically, public financing is directed solely to facilitate the development of technology and to address technological problems (Hänninen, 2007). Hänninen developed the concept of perfect technology syndrome to describe the intention to achieve the ultimate level in the development of technology. He indicated that perfect technology syndrome may lead to market delay. Ernst and Soll (2003) proposed an integrated R&D portfolio model to emphasise the integration between market requirements and technological capabilities. Based on these perspectives, we proposed an initial hierarchical ITDP project selection model based on AHP in Huang et al. (2008), and emphasised not only the technological aspect but also other aspects necessary to consider in an initial ITDP project selection model based on AHP.

We reviewed relevant literature[2] as well as the current ITDP selection approach and interviewed eight experts from a technical advisory committee to examine the initial

ITDP model with regard to feasibility. We finally developed the hierarchical ITDP selection model as shown in Figure 5. Four aspects of the hierarchical model are as follows; the definitions of these criteria are presented in Table 2 (Huang et al., 2008):

1 S&T merit: the technological impacts of ITDP project, including the competitiveness of technology and its relevance.

2 Potential benefits: the expected ITDP project benefits for the entire country, including economic benefits and social benefits.

3 Project execution: the execution and implementation of the ITDP project, including the quality of the technical plan and availability of resources.

4 Project risk: possible risk of the ITDP project, including technical risk, development risk and commercial risk.

Figure 5 ITDP hierarchical selection model

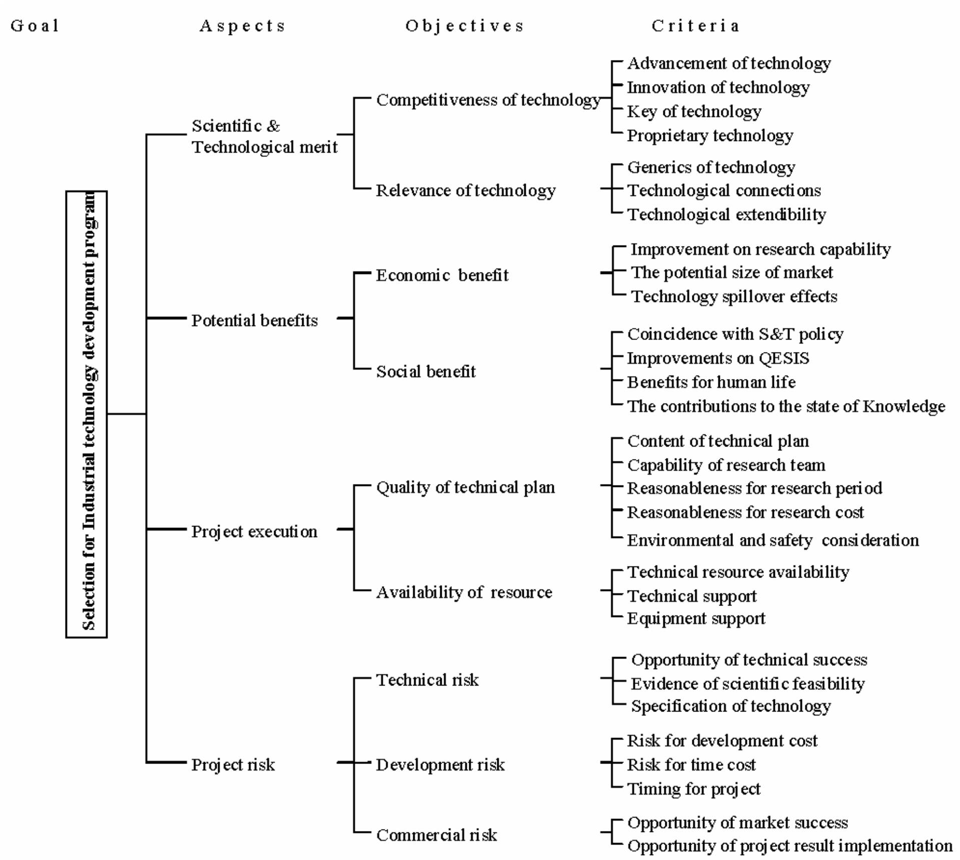


Table 2 The definition of ITDP criteria

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 extents 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
Contributions to the state of knowledge	The extents 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
Reasonableness for research period	The reasonableness of scheduling project period, permitting successful completion of the project objectives
Reasonableness for research cost	The reasonableness of scheduling project cost, permitting successful completion of the project objectives

Table 2 The definition of ITDP criteria (continued)

Criteria	*Definition*
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 organisational technology
Equipment support	The extents to which project can be supported by organisational 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 firm

4.2 The ITDP network model

The ITDP, one of the major TDP in Taiwan, aims to encourage industries to develop key innovative technologies and take part in 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, since 1999, 662 applications have been filed and 289 of these have been approved. Among the 289 sponsored projects, telecommunication and electronics-based projects account for the largest portion (44%). From 1997 to 2004, the ITDP's actual expenditure increased significantly from NT$2.85 billion to NT$10.70 billion (DoIT, 2006b). The ITDP has produced 300 patents, 562 patent applications, 997 technical reports and has held 201 technical conferences (DoIT, 2006c).

According to the Department of Industrial Technology (DoIT), there are 38 experts on the ITDP technical advisory committee. ITDP project evaluation involves two review processes. According to the decision criteria given by the DoIT, three to five experts with domain knowledge in each project area comprise a technical advisory committee and first review the technical feasibility and the expected returns of ITDP applications independently. Questions regarding technical uncertainties, market risks and lack of hard data often require these evaluations to proceed subjectively and intuitively. The review results of the technical advisory committee are approved (or not) in a final committee that consists of all 38 experts on the technical advisory committee.

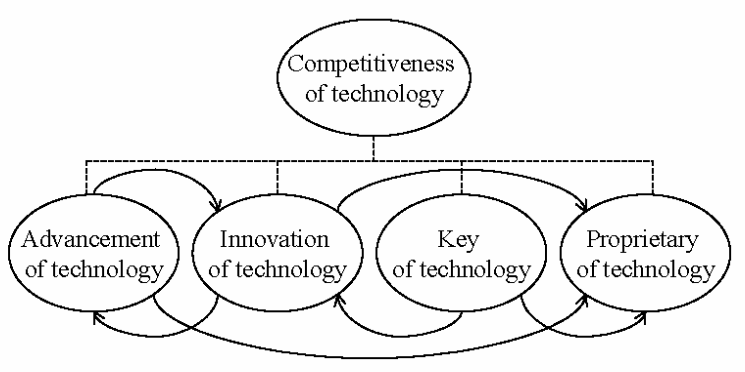
These experts require about two months reviewing projects; they utilise group discussion to form consensus decisions when evaluations are different. However, group discussion is usually time-consuming and some experts may conform to the judgements of the majority. Fuzzy ANP can integrate different expert judgements into a group consensus more easily than group discussion. Moreover, experts on the technical advisory committee can shorten review time by using a fuzzy ANP approach. Thus, DoIT can expedite the approval of projects through fuzzy ANP. Indeed, fuzzy ANP involves mathematical computational procedures and experts may need to take some time to calculate and rank criteria of alternatives; however, the computational procedure itself is relatively simple. From the perspective of methodology and application, fuzzy ANP may be an appropriate method in government-supported R&D project selection.

Based on the suggestions of experts on the technical advisory committee, interrelationships among criteria exist regarding the 'competitiveness of technology' shown in Figure 6. They are:

1 the feedback between advanced technology and innovative technology
2 the influence of innovative technology on proprietary technology
3 the influence of advanced technology on proprietary technology
4 the influence of key technology on both innovative technology and proprietary technology (see Figure 6).

Therefore, we modified the ITDP hierarchical model (Figure 5) to the ITDP network model (Figure 6) that includes dependence effects among evaluation criteria.

Figure 6 Dependence structure for 'competitiveness of technology'



4.3 Data collection and analysis

Questionnaires were sent to 24 ITDP experts on the technical advisory committee in order to evaluate the ITDP network model. All ITDP experts completed the questionnaire. The aim of the survey was to collect the committee members' weight judgements of the ITDP criteria and the relationships among criteria. As such, the questionnaires utilised pair-wise comparison of the relative importance of criteria using a scale from 1 to 9[3]. We used the triangular membership function and α-cuts to convert the expert judgements into fuzzy judgements. Considering that the less value the α-cut value has, the higher is uncertainty, we formulated all individual fuzzy comparison matrices based on the triangular membership function and α-cuts, and we then solved fuzzy eigenvalues and eigenvector at $\alpha = 0, 0.2, 0.4, 0.6, 0.8, 1$. After combining the priorities over all criteria, the overall importance weights of experts were determined. Subsequently, we used an average approach to integrate group fuzzy judgements.

5 Analysis of ITDP expert judgements

5.1 Overall weights of ITDP selection criteria and their implications

In the network model, the fuzzy weights based on the opinions of the technical advisory committee are summarised in Tables 3 and 4. Instead of displaying the results of each α, we only show the results for $\alpha = 0$ (the most uncertain judgement), $\alpha = 0.6$ (a more uncertain judgement) and $\alpha = 1$ (the least uncertain judgement). The results indicate that 'S&T merit' is the most important criterion when the technical advisory committee determines the value of technology R&D projects, whereas the criteria of 'project execution' and 'potential benefits' are important but relatively weaker. This finding is consistent with the results of Hsu et al. (2003) and Huang et al. (2008). In Taiwan, DoIT provides a huge amount of funding to encourage firms to develop advanced and innovative R&D projects. Thus, the technical advisory committee puts more emphasis on technology criterion and execution criterion. Because we do not consider an interdependence effect among the criteria in the first evaluation tier, the expert judgements are the same in the hierarchical and network models.

As shown in Table 4, the technical advisory committee places more emphasis on 'competitiveness of technology', 'economic benefit', 'quality of the technical plan' and 'availability of resources' in the second evaluation tier. According to the business competitiveness index of the World Economic Forum (WEF), Taiwan's business competitiveness rank is gradually downgrading, moving from 13th in 2004 to 21st in 2006 (WEF, 2007). Taiwan's core knowledge and innovation derives from technology R&D for industries, particularly in Taiwan's high-tech industries. To promote Taiwan's business competitiveness, technical advisory committee understandably places the most emphasis on the competitiveness of industrial technology. One particular strategy ITDP employs is to encourage local companies to upgrade their technology competitiveness via internationalisation (DoIT, 2006c). The proposed technology must have a strong potential to generate substantial benefits to the country that extend significantly beyond the direct benefits to the applicant companies. Therefore, 'economic benefit' is also very important in ITDP project selection. Moreover, there were 662 projects submitted for evaluation between 1999 and 2005 (DoIT, 2006a). The technical advisory committee must review a great number of submitted projects based on their technical plans, which naturally places a higher weight on the 'quality of the technical plan'. Similarly, there is no interdependence among the criteria in the second evaluation tier, so expert judgements in both models are the same.

Table 3 ITDP criteria ranking of the first evaluation tier

Criteria	*Ranking*	$\alpha = 0$			$\alpha = 0.6$			$\alpha = 1$		
S&T merit	1	0.391	0.424	0.450	0.414	0.424	0.436	0.424	0.424	0.424
Potential benefits	3	0.188	0.202	0.228	0.197	0.202	0.214	0.202	0.202	0.202
Project execution	2	0.193	0.218	0.236	0.208	0.218	0.225	0.218	0.218	0.218
Project risk	4	0.131	0.156	0.166	0.144	0.156	0.159	0.156	0.156	0.156

Notes: By defining different α-cut value, individual ITDP expert judgements can be indicated by TFNs. Using Lambda-Max method (Csutora and Buckley, 2001), group judgements are described as a triplet $(\alpha_1, \alpha_2, \alpha_3)$ after synthesising all priorities in ITDP selection model.

Table 4 ITDP criteria ranking of the second evaluation tier

Criteria	*Ranking*	$\alpha = 0$			$\alpha = 0.6$			$\alpha = 1$		
Competitiveness of technology	1	0.306	0.339	0.368	0.330	0.339	0.352	0.339	0.339	0.339
Relevance of technology	5	0.073	0.084	0.092	0.080	0.084	0.087	0.084	0.084	0.084
Economic benefit	2	0.133	0.148	0.171	0.144	0.148	0.158	0.148	0.148	0.148
Social benefit	7	0.047	0.054	0.063	0.051	0.054	0.057	0.054	0.054	0.054
Quality of technical plan	3	0.108	0.126	0.143	0.119	0.126	0.132	0.126	0.126	0.126
Availability of resource	4	0.076	0.093	0.101	0.086	0.093	0.096	0.093	0.093	0.093
Technical risk	6	0.060	0.077	0.088	0.070	0.077	0.081	0.077	0.077	0.077
Development risk	9	0.025	0.032	0.040	0.029	0.032	0.034	0.032	0.032	0.032
Commercial risk	8	0.034	0.046	0.052	0.041	0.046	0.048	0.047	0.046	0.047

When we first ignore the interdependence among criteria in the third evaluation tier, 'key of technology' receives the highest weight, followed by 'advancement of technology', 'potential size of the market', 'proprietary technology' and 'innovation of technology'. When we consider the interrelationship among criteria in the network model, 'key of technology' receives the highest weight, followed by 'innovation of technology', 'advancement of technology', 'potential size of the market' and 'improvements in research capability'. The ranking of criteria differs except for 'key of technology'. This finding reflects the objectives and responsibilities of TDP in Taiwan, i.e.:

1. to develop key technologies and components to speed up the upgrading of traditional industries
2. to develop innovative technologies to assist in setting up new industries and to stimulate existing industries (DoIT, 2006d).

Since 97% of companies in Taiwan are small-sized firms, domestic R&D capacity may be limited. Technology from abroad has played an important role in Taiwan's technological development. For example, the Electronic Research and Service Organization (ERSO) of the Industrial Technology Research Institute is deeply involved in international technology transfer, often identifying key technologies and sub-licensing them to local firms (Lee and Chen, 2006). By developing a key technology, firms can draw on the critical nature of technology and reduce reliance on the introduction of foreign technology to improve their R&D capability. ITDP experts on the technical advisory committee put the highest weight on 'key of technology', reflecting their concerns about upgrading traditional industries by improving technology in order to dominate industrial competitiveness (DoIT, 2006d).

5.2 Comparing weights of ITDP selection criteria in four areas

Recall that 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. We analyse the judgements of the technical advisory committee across these four areas at $\alpha = 0, 0.2, 0.4, 0.6, 0.8, 1$. In the network model, as noted in Table 5, the committees for telecommunication and electronics, materials and chemical engineering as well as biotechnology and pharmaceuticals all emphasise 'S&T merit'. This indicates that experts in these three areas emphasise technological considerations. However, the committee for mechanical engineering and aeronautics emphasises 'potential benefits'. This may be because applicants in this area place more emphasis on technological applications. Thus, experts consider whether potential benefits can be obtained from technology application.

The 'competitiveness of technology' is the most important criterion in the second evaluation tier for all four ITDP areas. Because there is no interdependence among the criteria in the first and second evaluation tiers, the expert judgements of the hierarchy model in four main areas are the same as those of the network model in four main areas. 'Key of technology' receives the highest weight for all four areas in the third evaluation tier in the network model. This finding is the same as that of the technical advisory committee. The objective and responsibility of Taiwan's TDP is to develop critical technologies in order to accelerate the upgrading of traditional industries (DoIT, 2006d).

Table 5 ITDP criteria ranking of the first evaluation tier in four areas

Criteria	$\alpha = 0$			$\alpha = 0.6$			$\alpha = 1$		
Telecommunication and electronics									
S&T merit[1]	0.432	0.467	0.500	0.456	0.467	0.481	0.467	0.467	0.467
Potential benefits[4]	0.128	0.139	0.163	0.134	0.139	0.148	0.139	0.139	0.139
Project execution[2]	0.231	0.256	0.270	0.247	0.256	0.262	0.256	0.256	0.256
Project risk[3]	0.119	0.139	0.150	0.130	0.139	0.142	0.139	0.139	0.139
Mechanical engineering and aeronautics									
S&T merit[2]	0.278	0.284	0.337	0.284	0.284	0.309	0.284	0.284	0.284
Potential benefits[1]	0.290	0.308	0.338	0.300	0.308	0.322	0.308	0.308	0.308
Project execution[4]	0.161	0.194	0.203	0.179	0.194	0.197	0.194	0.194	0.194
Project risk[3]	0.183	0.213	0.228	0.199	0.213	0.218	0.213	0.213	0.213
Materials and chemical engineering									
S&T merit[1]	0.374	0.427	0.443	0.410	0.427	0.435	0.427	0.427	0.427
Potential benefits[2]	0.233	0.251	0.276	0.246	0.251	0.262	0.251	0.251	0.251
Project execution[3]	0.138	0.163	0.185	0.152	0.163	0.170	0.163	0.163	0.163
Project risk[4]	0.127	0.160	0.169	0.145	0.160	0.162	0.160	0.160	0.160
Biotechnology and pharmaceuticals									
S&T merit[1]	0.390	0.398	0.399	0.397	0.398	0.399	0.398	0.398	0.398
Potential benefits[3]	0.200	0.216	0.247	0.212	0.216	0.230	0.216	0.216	0.216
Project execution[2]	0.212	0.235	0.262	0.228	0.235	0.246	0.235	0.235	0.235
Project risk[4]	0.133	0.151	0.158	0.142	0.151	0.152	0.151	0.151	0.151

Note: 1, 2, 3 and 4 represent criteria ranking.

In the hierarchy model, overall criteria rank differently in all four areas. 'Advancement of technology' receives the highest weight in telecommunication and electronics. 'Improvements in research capability' receives the highest weight in mechanical engineering and aeronautics. 'Proprietary technology' receives the highest weight in materials and chemical engineering. 'Key of technology' is most important in biotechnology and pharmaceuticals. Other criteria in the hierarchy model show differences across the four areas. Due to interdependence among criteria in the third evaluation tier, expert judgements across the four areas are different in the hierarchy model as opposed to the network model.

Overall, ITDP experts on technical advisory committees across the four main areas emphasise technology, according to the network model. However, different industrial areas must consider technology differently with regard to R&D. For example, the information technology and semiconductor industries are the leading industries in Taiwan. The industrial strategies in the two industries have gradually changed from production cost-based to innovation value-based. Thus, 'innovation of technology' is the second highest consideration for ITDP experts in telecommunication and electronics. The biotechnology industry is a relatively new technology industry in Taiwan and companies in this industry must invest great amounts of technical efforts and resources. Business benefits are also difficult to obtain in the short term. Thus, a firm's internal technical support is relatively important for the development of R&D projects. Therefore, ITDP experts cite 'technical support' as the second highest consideration in biotechnology and pharmaceuticals. The nature of technology developments and other distinct industrial characteristics are key foci of R&D development. That is why ITDP experts across these four areas consider different technological aspects when evaluating ITDP proposals.

6 Summary and conclusions

For R&D project selection in the public sector, it is very important to consider the interdependent relationships among criteria. Previous studies such as Hsu et al. (2003) and Wang et al. (2005) used fuzzy AHP to select technology R&D projects. However, the fuzzy AHP does not deal with interdependency among evaluation criteria. R&D projects are influenced by complicated evaluation criteria and these evaluation criteria may interact. In this study, we applied a fuzzy ANP approach to technology R&D project selection. As such, this is a new application of fuzzy ANP to government-supported R&D project selection. Understanding reviewer judgements is important for private firms to obtain government funding for R&D projects. Also, the government-supported R&D project selection process will be more transparent through the use of fuzzy ANP and its generation of weighted evaluation criteria. In this study, all ITDP reviewers on the technical advisory committee expressed the view that our study is highly feasible and urged us to present our research results at the upcoming ITDP annual meeting.

The results of this study reveal the following:

1 The technology merit criterion overall emphasised by ITDP experts is the most important consideration criterion; however, ITDP experts across the four main areas show different judgements regarding the importance of other criterion.

2 The ITDP general experts and the ITDP area experts all emphasise the competitiveness of technology.

3 When interdependence exists among evaluation criteria, ITDP general experts and ITDP area experts all emphasise the key of technology.

4 Finally, after incorporating dependence effects in the network structure, ITDP general experts and ITDP area experts show judgement differences. That is, dependence effects change importance-rankings for ITDP evaluation criteria; technology lead is an important consideration in ITDP project selection.

This study is a novel application of fuzzy ANP to government-supported R&D project selection. To our best knowledge, there is no study that uses fuzzy ANP to model the selection of government-supported R&D project selection. We have created a better understanding of fuzzy ANP by extending it to R&D project selection in the public sector. Despite all the care given to this study, there are limitations of the present study that should be noted and addressed in any future research. First, although approved ITDP projects can help validate our research results, we were unable to access official data on approved ITDP projects because of administrative concerns regarding confidentiality. Further studies on government-supported R&D project selection may employ survey methods to collect input-output information regarding approved projects to validate research results. Data envelopment analysis (Charnes, et al., 1978) may be an appropriate analytical approach to compare performance across projects. Second, the judgement accuracy of ITDP experts is important for ITDP selection. The performance of approved ITDP projects may be useful to evaluate the judgement accuracy of ITDP experts. Further studies in government-supported R&D project selection that incorporate approved project performance may be necessary to assess the accuracy of expert judgement for the sake of improving expert judgement quality.

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Notes

1 We developed this hierarchy model based on the AHP (Saaty, 1980), one of the most popular and powerful methods for modelling group decision-making. The hierarchy model is presented in Huang et al. (2008).

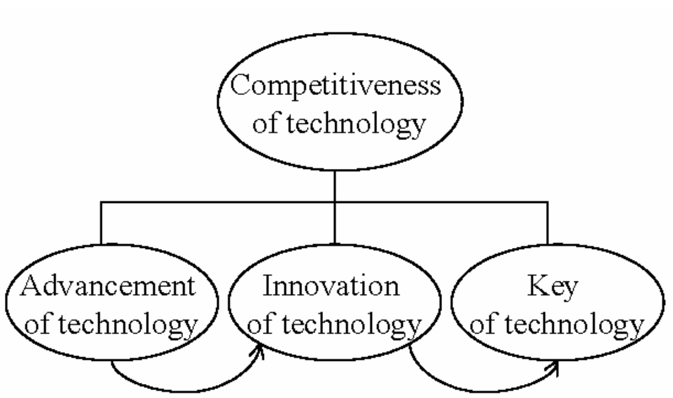
2 Our review included Horesh and Raz (1982), Mustafa (1991), Gaber et al. (1992), Zopounidis (1994), Santhanam and Kyparisis (1995), Lee and Om (1996), Pandy and Jang (1996), Al-Mazidi and Ghosn (1997), Balachandra and Friar (1997), Kutlaca (1997), David et al. (2000), Ballesteros and Rico (2001), Coldrick et al. (2002), Stewart and Mohamed (2002), Ernst and Soll (2003), Hsu et al. (2003), Feldman and Kelly (2003a, 2003b), ATP (2004), Astebro (2004), DoIT (2004), Kondo (2004), and Yapp (2004).

3 We use linguistic terms to represent expert assessments. For example, experts use 1 for 'equal importance', 9 for 'absolute importance' and other values for intermediate values between the two former criteria judgements. We utilise a set of TFNs from 1 to 9 to represent their importance. TFNs (8, 9, 10) for 'extremely important' and (1, 1, 2) for 'extremely unimportant' are used to capture the fuzzy range of expert judgement.

Appendix A

We use a fuzzy ANP example to demonstrate the weight calculations of inter-related criteria. Three elements in the criterion 'competitiveness of technology' show dependencies in Figure A1. We go through three steps mentioned in Section 2.3 to determine interdependent weights $w_{\alpha}^{\text{inter}}$.

Figure A-1 A fuzzy ANP example



Determining fuzzy weights in the study of Csutora and Buckley (2001)

First, assume there is no dependence among three elements in Figure A1. The priority vectors of three elements will be estimated based on Step 1 to Step 5, mentioned in Section 2.3. Table A1 notes possible fuzzy weights.

Table A1 Fuzzy weights of the three elements

Element	*Fuzzy weights*
Advancement of technology	(0.57, 0.59, 0.59)
Innovation of technology	(0.23, 0.25, 0.27)
Key of technology	(0.15, 0.16, 0.19)

Determining the inner dependence matrix

Second, estimate inner dependence matrix W_{α}^{inner} in Figure A1. The W_{α}^{inner} consists of priority vectors of elements with inner dependence. Determine inner dependence among three elements. The priority vectors of dependent elements will be estimated based on Step 1 to Step 5, mentioned in Section 2.3. Table A2 notes one possible inner dependence matrix of the competitiveness of technology.

Table A2 Inner dependence matrix of technology competitiveness

Element	*Advancement of technology*	*Innovation of technology*	*Key of technology*
Advancement of technology	(1, 1, 1)	(0.58, 0.67, 0.67)	0
Innovation of technology	0	(0.33, 0.33, 0.38)	(0.71, 0.75, 0.75)
Key of technology	0	0	(0.25, 0.25, 0.27)

Determining the interdependent weights

The calculation of $w_{\alpha}^{\text{inter}}$ by $w_{\alpha}^{\text{inter}} = W_{\alpha}^{inner} \times w_{\alpha}^{*}$ is shown from equations (A1) to (A3). Table A3 shows the interdependent weights of three elements.

$$w_l^{\text{inter}} = \begin{pmatrix} 1 & 0.58 & 0 \\ 0 & 0.33 & 0.71 \\ 0 & 0 & 0.25 \end{pmatrix} \times \begin{bmatrix} 0.57 \\ 0.23 \\ 0.15 \end{bmatrix} = \begin{bmatrix} 0.70 \\ 0.18 \\ 0.04 \end{bmatrix} \tag{A1}$$

$$w_m^{\text{inter}} = \begin{pmatrix} 1 & 0.67 & 0 \\ 0 & 0.33 & 0.75 \\ 0 & 0 & 0.25 \end{pmatrix} \times \begin{bmatrix} 0.59 \\ 0.25 \\ 0.16 \end{bmatrix} = \begin{bmatrix} 0.76 \\ 0.20 \\ 0.04 \end{bmatrix} \tag{A2}$$

$$w_u^{\text{inter}} = \begin{pmatrix} 1 & 0.67 & 0 \\ 0 & 0.38 & 0.75 \\ 0 & 0 & 0.27 \end{pmatrix} \times \begin{bmatrix} 0.59 \\ 0.27 \\ 0.19 \end{bmatrix} = \begin{bmatrix} 0.77 \\ 0.25 \\ 0.05 \end{bmatrix} \tag{A3}$$

Table A3 Interdependent weights of three elements

Element	*Interdependent weights*
Advancement of technology	(0.70, 0.76, 0.77)
Innovation of technology	(0.18, 0.20, 0.25)
Key of technology	(0.04, 0.04, 0.05)