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ORIGINAL ARTICLE

Strategic justification of advanced manufacturing technology using an extended AHP model

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Abstract The hybrid process and group decision-making are two critical requisites for justification of advanced manufacturing technology (AMT). This study proposes an extended analytic hierarchy process model for AMT justification, which revises the way of obtaining values of pairwise comparisons in order to take into account both tangible and intangible criteria. Additionally, in group decision, the weights of decision makers (DMs) are required while aggregating all DMs' priorities of alternatives. A novel technique for determining DMs' weights is proposed. In addition, the application of the proposed model to a Taiwanese case is used to verify the availability of this model.

Keywords Technology selection · AMT justification · Analytic hierarchy process · Group decision

1 Introduction

Uncertainties in the current economic environment and the ever-changing consumer preferences have significantly increased the importance of implementing advanced manufacturing technology (AMT) [1–10]. AMT has been recognized as a strategic tool that gives companies a competitive advantage [4, 10–15]. On the other hand, Swink and Nair [8] found that the debate over the impact of AMT based on empirical evidence continues. Hayes and Pisano [16] reported the dissatisfaction often expressed by practitioners with regard to the introduction of different new AMTs. Hottenstein, Casey, and Dunn [17] argued that many AMT projects failed to meet the expectations of those who adopt them. This fact indicates the importance of selecting an appropriate AMT. Only "right" technologies can create significant competitive benefits; on the contrary, "inappropriate" technologies can reduce the competitiveness of companies.

Canada [1], Meredith and Suresh [5], Raafat [6], and Son [7] provide comprehensive bibliographies on AMT justification. As Raafat [6] notes, justifying the acquisition of a new technology is a complex and multi-dimensional process. Torkkeli and Tuominen [10] concluded that AMT justification becomes more difficult with the increasing number and complexity of technologies that involve an uncertain environment, time-consuming processes, inadequate information, and subjective factors. This indicates that as technology has advanced and the manufacturing environment has become more dynamic, manufacturing systems have become more complex, and the results of AMT have become more difficult to quantify, analyze, and predict [4]. Therefore, it is necessary to employ an appropriate evaluation method that can assist decision makers (DMs) in selecting the technology best suited to their operations and business objectives.

Various models proposed in literature have been adopted in AMT justification [1, 5–7], and there is consensus on two key points: (1) These models constantly shift their focus from cost/finance to strategy considerations such that both tangible (economic) and intangible (strategic) factors are taken into consideration when justifying AMT; and (2) the hybrid approach is favored since conventional financial approaches (i.e., discounted cash flows, DCF) cannot

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measure intangible benefits. The hybrid approach includes both economic and strategic justification processes [12].

On the other hand, in the AMT selection process, the company's core competencies and requirements from different departments should be taken into consideration to ensure that the selected AMT serves all the functions of the company efficiently. Small and Chen's study on US manufacturers' use of various approaches confirmed the consensus and concluded that the participation of specific functional departments had significantly impacted on the success of AMT implementation [12]. Torkkeli and Tuominen [10], Mohanty and Deshmukh [13], and Chuu [18] emphasized the importance of group decision-making in AMT justification. Accordingly, we can conclude that a robust approach for AMT justification has two requisites: (1) a hybrid process that takes into account both tangible and intangible criteria and (2) participants from various departments involved in group decision-making on justifying AMT. The analytic hierarchy process (AHP) is a popular multiple criteria decision-making (MCDM) model; it provides a flexible framework that accommodates the above-mentioned requisites and has proved to be efficient in AMT selection [11–13, 18–20]. Nevertheless, some critiques of AHP have pointed out the issues of "unbalanced scale" and group decision aggregation [21].

Saaty's AHP [22] is a popular MCDM approach whereby the problem of decision-making is configured in a hierarchy and pairwise comparisons are performed to evaluate the relative importance/preference of criteria/objectives by using eigenvector or other simplified methods. DMs' pairwise comparisons were converted into corresponding values on the basis of the following scale: $\frac{1}{9}, \frac{1}{8} \cdots 1, 2 \cdots 8, 9$. The interval between scale values for the comparisons above "equally important" was (1, 9) and that for comparisons below "equal importance" was $(\frac{1}{9}, \frac{1}{2})$. The large difference between these two intervals, (1, 9) and $(\frac{1}{9}, \frac{1}{2})$, results in an "unbalanced scale" [21]. In literature, fuzzy set theory is a potential solution to the problem of an unbalanced scale [2, 14–28]. In current studies on fuzzy AHP, pairwise comparisons are treated as linguistic variables and are transformed into fuzzy numbers, particularly triangular fuzzy numbers (TFNs). Subsequently, two common methods are used to prioritize alternatives. The first method is to employ the fuzzy number arithmetic to replace Saaty's AHP computation; this method, however, has been criticized for causing fuzziness of fuzzy numbers to expand. In the second method, first fuzzy ranking is employed to transform the fuzzy numbers into crisp values that are evenly distributed within a certain range; then, Saaty's AHP computation procedure is carried out. This method avoids the above fuzziness expansion and improves the "unbalanced scale"; therefore, the model proposed in this article will adopt the second method, and an extended version of the model will be engaged as follows.

In Saaty's AHP, pairwise comparisons with the same assignments are transformed into an identical value for subsequent computations; for example, "moderate importance" is always assigned a value of 3. This situation also exists in the available fuzzy AHP models. Nevertheless, this view is quite unsatisfactory when DMs perform pairwise comparisons under various assurance levels. The assurance level indicates the confidence of a DM in his/her pairwise comparison. While performing pairwise comparisons, a DM is often certain of only some of his/her judgments. For example, a DM with expertise in finance, but who is unfamiliar with production, can perform more credible pairwise comparisons about finance than about manufacturing. Therefore, it is more reasonable to assume that the same pairwise comparisons with various assurance levels yield various values specified in the assurance principle. Hence, when a DM with financial expertise assigns values to the pairwise comparisons, the values assigned to financial criteria with a higher assurance level are larger than those assigned to the manufacturing criteria with a lower assurance level. Unfortunately, the body of fuzzy AHP literatures that discusses this issue is very small. Thus, the first objective of our extended AHP model for AMT justification is to conform to the noted requisites for justifying AMT and to solve both the unbalanced scale and assurance principle existing in Saaty's AHP.

Furthermore, AMT justification is usually carried out on the basis of group decision by various specialists. In a group decision environment, each DM is asked to make individual judgments that are later aggregated. The weighted geometric mean method (WGMM) and weighted arithmetic mean method (WAMM) are two typical approaches for aggregating group decisions [29–35]. However, when WGMM or WAMM is applied for aggregating group decisions, determining the weights to be assigned to a DM becomes a critical issue. In general, the weight for a DM represents the extent of his/her contribution to the final decision. However, there is no standard approach for determining these weights. Therefore, the second objective of our model is to utilize the assurance levels of one DM for his/her pairwise comparisons as the baseline to determine the weights. The higher a DM's confidence, the greater would be his/her contribution in making the final decision.

Accordingly, the proposed extended AHP model comprises two phases in the process of AMT justification: (1) Each DM individually evaluates alternatives by using the revised AHP model in order to prioritize alternatives; (2) then, each DM's individual priorities are aggregated into a final set of priorities on the basis of the weights assigned to the DMs, and this set of priorities is used to make the final decision. To illustrate the computation and feasibility of the proposed model, the case of a Taiwanese motorcycle manufacturer will be discussed in detail in this paper.

The rest of this paper is organized as follows. The extended AHP model, including the procedures for evaluating each DM's priorities and determining the weights of DMs for aggregating decisions, is first outlined in Section 2. The applicability of this extended AHP model to a Taiwanese case is discussed in Section 3. Finally, the conclusions are listed in Section 4.

2 An extended AHP model for AMT justification

The model for AMT justification proposed in this paper is an extension of Saaty's AHP. The extended model was developed by using fuzzy theory under a group decision environment wherein (1) DMs individually evaluate alternatives by using a revised fuzzy AHP model and (2) the individual evaluations are aggregated into a common set of priorities for making a decision. The details of these two phases are discussed separately in the following subsections.

2.1 Phase I: DMs individually evaluate AMT alternatives by using the revised AHP model

This article proposes improving Saaty's AHP in three ways: (1) use the fuzzy set method to solve the problem of AHP's unbalanced scale, (2) introduce the assurance levels of the DMs on their pairwise comparisons to improve the assurance principle, and (3) increase the AHP's capability of considering both tangible and intangible criteria for conforming to the hybrid process requisite for AMT justification. Suppose n DMs and m alternatives exist and E_{ki} denotes the priority of alternative i from DM$_k$, where $i=1, 2,\ldots, m$ and $k=1, 2,\ldots, n$. The following revisions were introduced.

1. Revision 1: Transform objective quantities into relative values for tangible criteria

   Since tangible criteria have objective quantities, for example, acquisition cost, subjective pairwise comparison need not be performed, and the assurance principle does not exist in tangible criteria. Then Eq. 1 is defined to compute the values of pairwise comparisons on tangible criteria on the basis of the principle of relative strength. Let c_t denote the objective quantity of criteria t and Z^t_{xy} the relative value of tangible criterion x over tangible criterion y, where

   $$Z^t_{xy} = \left[1 - e^{-\left(c_x/c_y\right)/3.7}\right] \times 9 \tag{1}$$

   In the above equation, the relative strength was initially obtained by dividing c_x by c_y, and a risk-averse utility function was then introduced to transfer the relative strength to fit the interval (0, 9). The parameter, 3.7, is obtained through a discussion among the members of the decision-making team of the target company.

2. Revision 2: Compute the pairwise comparison values for intangible criteria

   Let Z^{nt}_{xyk} be the representative value of the pairwise comparison of intangible criterion x over intangible criterion y from DM$_k$. The procedure for deriving Z^{nt}_{xyk} is explained as follows.

   (a) Linguistic pairwise comparisons are converted into TFNs, with the membership functions falling between (0, 1) according to Table 1, where $\widetilde{c}_{xyk}$ is the pairwise comparison of criterion x over criterion y from DM$_k$. These rules listed in Table 1 are derived from Chen and Hwang's study [36].

   (b) The fuzzy value, Z_{xyk}, of the corresponding $\widetilde{c}_{xyk}$ is computed on the basis of Baldwin and Guilds's fuzzy ranking method [37].

   Supposed that $\widetilde{c}_{xyk} = \left\{\left(x_D, \mu_{c_{xyk}}(x_D)\right)\right\}$ and $\widetilde{1} = \{(x_1, \mu_1(x_1))\}$, then the fuzzy value of $\widetilde{c}_{xyk}$, named Z_{xyk}, is defined as

   $$Z_{xyk} = \sup_{x_D, x_1}\left\{\min\left[\mu_{c_{xyk}}(x_D), \mu_1(x_1), \mu_{P_{D1}}(x_D, x_1)\right]\right\}, \tag{2}$$

where

$$\mu_{P_{D1}} = \begin{cases} (x_D)^{0.5} - (x_1)^{0.5}, & \text{assurance level is low,} \\ x_D - x_1, & \text{assurance level is medium,} \\ (x_D)^2 - (x_1)^2, & \text{assurance level is high.} \end{cases}$$

Since the membership functions of TFNs used in this study are all piecewise linear functions, $\mu_{O_{xyk}}$ is obtained through the following simplified computation [37] with the TFN defined as $\widetilde{1} = (0.45, 0.5, 0.55)$ and $\widetilde{c}_{xyk} = (\lambda, \delta, \gamma)$:

$$\begin{cases} \text{Low assurance level} : Z_{xyk} = \left[\delta - Z_{xyk} \times (\delta - \gamma)\right]^{1/2} - \left[0.45 + Z_{xyk} \times 0.05\right]^{1/2}, \\ \text{Medium assurance level} : Z_{xyk} = \frac{\delta - 0.45}{1 + (\delta - \gamma) + 0.05}, \\ \text{High assurance level} : Z_{xyk} = Z^2_{xyk}\left[0.05^2 - (\delta - \gamma)^2\right] + \left[Z_{xyk}(1 + 2\delta(\delta - \gamma) + 2 \times 0.45 \times 0.05\right] + 0.45^2 - \delta^2. \end{cases} \tag{3}$$

Table 1 Linguistic terms and membership functions for pairwise comparisons

Linguistic term	Fuzzy number	Membership function
Extremely unimportant (EU)	$\widetilde{1/9}$	(0, 0, 0.05)
Intermediate values between $\widetilde{1/7}$ and $\widetilde{1/9}$	$\widetilde{1/8}$	(0, 0.05, 0.1)
Very unimportant (VU)	$\widetilde{1/7}$	(0.05, 0.1, 0.15)
Intermediate values between $\widetilde{1/5}$ and $\widetilde{1/7}$	$\widetilde{1/6}$	(0.125, 0.175, 0.225)
Essentially unimportant (EU)	$\widetilde{1/5}$	(0.2, 0.25, 0.3)
Intermediate values between $\widetilde{1/3}$ and $\widetilde{1/5}$	$\widetilde{1/4}$	(0.275, 0.325, 0.375)
Moderate unimportance (MU)	$\widetilde{1/3}$	(0.35, 0.4, 0.45)
Intermediate values between $\tilde{1}$ and $\widetilde{1/3}$	$\widetilde{1/2}$	(0.4, 0.45, 0.5)
Equally important (EQ)	$\tilde{1}$	(0.45, 0.5, 0.55)
Intermediate values between $\tilde{1}$ and $\tilde{3}$	$\tilde{2}$	(0.5, 0.55, 0.6)
Moderate importance (MI)	$\tilde{3}$	(0.55, 0.6, 0.65)
Intermediate values between $\tilde{3}$ and $\tilde{5}$	$\tilde{4}$	(0.625, 0.675, 0.725)
Essentially important (EI)	$\tilde{5}$	(0.7, 0.75, 0.8)
Intermediate values between $\tilde{5}$ and $\tilde{7}$	$\tilde{6}$	(0.775, 0.825, 0.875)
Very vital importance (VI)	$\tilde{7}$	(0.85, 0.9, 0.95)
Intermediate values between $\tilde{7}$ and $\tilde{9}$	$\tilde{8}$	(0.9, 0.95, 1)
Extremely vital importance (XI)	$\tilde{9}$	(0.95, 1, 1)

(c) Z_{xyk}^{nt} is obtained by normalizing Z_{xyk} to fit the interval (0, 9) using the following equation.

$$Z_{xyk}^{nt} = \frac{Z_{xyk} - \min(Z_{xyk})}{\max(Z_{xyk}) - \min(Z_{xyk})} \times 9 \tag{4}$$

In this revision, the fuzzy methods, including TFN and fuzzy ranking, are introduced to solve the problem of an unbalanced scale in AHP. Otherwise, as shown in Eq. 2, the assurance levels of DMs are integrated into the computation of fuzzy value Z_{xyk} to deal with the assurance principle. Table 2 lists the values of all the available pairwise comparisons at each assurance levels. It is obvious that these values are evenly distributed between 0 and 9, thus avoiding the unbalanced scale.

3. Compute E_{ki} according to Z_{xy}^{t} and Z_{xyk}^{nt}

   After revisions 1 and 2, each DM has his/her own set of Z_{xyk}^{nt}, which is obtained on the basis of his/her subjective pairwise comparisons on intangible criteria, but only one set of Z_{xy}^{t} exists since Z_{xy}^{t} are derived from objective quantities of tangible criteria and are treated as each DM's evaluations. Subsequently, each DM's set of E_{ki} is acquired from related Z_{xy}^{t} and Z_{xyk}^{nt} by using the eigenvector method and the hierarchical composition in Saaty's AHP. The computations of E_{ki} are illustrated in Section 3.3.

2.2 Phase II: Aggregating group decisions

After deriving each DM's set of E_{ki} in the first phase, the second phase uses the WGMM to aggregate all DMs' sets of E_{ki} into a common set of E_i to obtain a final decision, and the DMs' assurance levels in their pairwise comparisons are adopted as the baseline to determine each DM's weight used in the WGMM. The higher a DM's assurance level, the greater is his/her contribution to the final decision. On the basis of this concept, this study proposes the following approach to derive the weights of the DMs.

Let w_k be the weight of DM$_\text{k}$. The steps of obtaining w_k are listed below:

1. The linguistic assurance is converted into the assurance level of DM$_k$ for the pairwise comparison of criterion x over criterion y, that is, a_{xyk}, with the scale ranging from 0 to 1. In this study, the values 1, 0.5, and 0 are adopted to represent high, medium, and low assurance levels, respectively.
2. Each DM's assurance levels are grouped into several matrices, called 'assurance matrices', on the basis of the AHP hierarchy, which is in keeping with the AHP approach.
3. The maximum eigenvalues, λ_{xyk}^{a}, of each assurance matrix from DM$_k$ are computed.

   Since the interval of λ_{xyk}^{a} changes with the size of the matrix, λ_{xyk}^{a} is converted into a relative value, denoted as λ_{xyk}^{r}, through Eq. 5.

$$\lambda_{xyk}^{r} = [\lambda_{xyk}^{a} - \min(\lambda_{xyk}^{a})]/[\max(\lambda_{xyk}^{a}) - \min(\lambda_{xyk}^{a})]. \tag{5}$$

The maximum of λ_{xyk}^{a}, $\max(\lambda_{xyk}^{a})$, is arrived when all the elements in the assurance matrix except those in the

Table 2 The values of pairwise comparisons to the three various assurance levels

Pairwise comparison	Assurance level		
	High	Medium	Low
Extremely vital importance (XI)	9.000	7.136	5.528
Intermediate values between VI and XI	8.481	6.950	5.470
Very vital importance (VI)	7.838	6.596	5.282
Intermediate values between EI and VI	6.929	6.065	4.993
Essentially important (EI)	6.085	5.534	4.691
Intermediate values between MI and EI	5.308	5.003	4.375
Moderate importance (MI)	4.599	4.471	4.043
Intermediate values between EQ and MI	4.165	4.117	3.811
Equally important (EQ)	3.763	3.763	3.570
Intermediate values between MU and EQ	3.393	3.409	3.319
Moderate unimportance (MU)	3.055	3.055	3.055
Intermediate values between EU and MU	2.610	2.524	2.633
Essentially unimportant (EU)	2.240	1.993	2.170
Intermediate values between VU and EU	1.947	1.462	1.651
Very unimportant (VU)	1.732	0.931	1.049
Intermediate values between EU and VU	1.634	0.577	0.575
Extremely unimportant (EU)	1.571	0.223	0.000

diagonal are equal to 1, and the λ^{a}_{xyk} reaches its minimum, $\min(\lambda^{a}_{xyk})$, while all the elements of the assurance matrix, except those in the diagonal, are equal to 0.

4. λ^{a}_{xyk} is normalized on the basis of all DMs' λ_{xyk} for one preference matrix to demonstrate the relative strengths of assurances among DMs.

$$\lambda^{na}_{xyk} = \lambda^{r}_{xyk} \Big/ \sum_{k=1}^{k} \lambda^{r}_{xyk}. \tag{6}$$

5. All λ^{na}_{xyk} of DM_k are aggregated through the hierarchical structure of the decision-making problem, in order to obtain w_k. The computational process is identical to the weights aggregation of Saaty's AHP method.
6. Aggregate all DMs' sets of E_{ki} into the common set of E_i through Eq. 7.

$$E_i = \prod_{k=1}^{n} (E_{ki})^{w_k}. \tag{7}$$

As shown, one DM's weight is derived on the basis of its maximum eigenvalue λ^{a}_{xyk} for the corresponding assurance matrices. Thus, the higher the assurance level in one assurance matrix, the larger the λ^{a}_{xyk}; this result conforms to the definition of a DM's weight in this study.

3 Application of the model to a Taiwanese case

In order to verify the feasibility of the proposed model, in this study, a Taiwanese company, which manufactures motorcycle parts, is targeted. The application of the model is illustrated in the following four subsections: (1) the hierarchy of criteria used in the Taiwanese case, (2) the collection of objective data and pairwise comparisons, (3) the computation of each DM's set of E_{ki}, and (4) the determination of DM's weights and the aggregation of E_{ki} in order to obtain the final decision.

3.1 The hierarchy of criteria used in the Taiwanese case

As stated by Torkkeli and Tuominen [10], the aim of AMT selection is to obtain new know-how techniques, components, and systems that help increase companies' competitiveness in terms of products, services, and process effectiveness or to come up with completely new solutions for improving manufacturing efficiency. Consequently, research in technology justification shifts its focus from economy to strategy [4, 10–15, 19].

TJTE, the target company, is a joint venture enterprise between KYM, a Taiwanese motorcycle manufacturing company, and TD, a Japanese mechanical company. TJTE supplies motorcycle parts mainly to KYM. KYM had 35.2% of the Taiwan motorcycle market share in 2008 and was the leader in the Taiwan motorcycle market for eight consecutive years. TD also provides research and development support to TJTE.

A motorcycle model is usually on sale for 3 to 5 years and is then replaced by a new model. The new model generally retains a few parts of the out-of-date model. In general, TJTE supplies motorcycle parts of one model for approximately 10 years, which can be divided into two periods: (1) The flourishing period: During the first 3 to 5 years, demand stems mainly from the sale of the motorcycle model and remains high; (2) the maintenance period: In the period after the motorcycle model is withdrawn from the market, demand exists only for repair parts, but it decreases annually.

TJTE considers purchasing new equipment for producing the cam shaft holder (CSH) used for four-stroke cylinders matched with related cycles for absorption, compression, explosion, and emission. The CSH is installed on the fuel boxes of motorcycles with a sensor to inspect the fuel volume. The existing manufacturing equipment for CSH is a dedicated and advantageous machine that ensures lower production time and labor cost. Nevertheless, TJTE has to spend a considerable amount of time to replace some parts of the dedicated machines when shifting production from one type of a CSH to another type. Since various motorcycle models comprise various types of CSH, the manufacturing shift occurs very often, thereby resulting in a waste of time. Therefore, TJTE plans to purchase new manufacturing equipment for CSH production. For this, three alternatives are available, namely Computer Numerical Control (CNC) equipment, flexible equipment, and original dedicated equipment. As shown in Tables 4 and 5, CNC equipment and flexible equipment ensure more production flexibility and less acquisition, manufacturing, and quality costs in comparison to dedicated equipment, while only the prevention cost is lower in case of dedicated equipment.

Four DMs, including the CEO, a production manager, a sales manager, and a financial manager, were invited to join the decision-making team. After discussions among the team members, the framework for the criteria used in their justification was established (Fig. 1). The criteria include three major categories: cost, flexibility, and quality. The cost category includes acquisition cost, maintenance cost, and production cost. In addition, three kinds of flexibility are covered: volume, routing, and expansion. The quality category consists of internal failure cost, external failure cost, appraisal cost, and prevention cost. After examining TJTE's existing data, it was found that only the data regarding cost category were available. Thus, the criteria in the cost category are treated as tangible criteria and the criteria in flexibility and quality category as intangible criteria.

3.2 The collection of objective data and pairwise comparisons

After establishing the hierarchical structure of the criteria, DMs separately perform pairwise comparisons with different assurance levels to determine the importance of the criteria. The pairwise comparisons regarding layers 1 and 2 are listed in Table 3. The comparisons among alternatives in layer 3 are classified into tangible and intangible criteria. For tangible criteria (i.e., acquisition cost, throughput), the comparisons among alternatives were made on the basis of Eq. 1 to obtain Z^{t}_{xy}. High assurance levels were assigned to these comparisons among alternatives because there was no ambiguity in the comparisons made using the objective data. In the TJTE case, the objective quantities were collected only for the cost category (Table 4).

Regarding intangible criteria (i.e., expansion flexibility), all the DMs held a meeting to jointly perform pairwise comparisons among these alternatives (Table 5). Since the above pairwise comparisons were performed according to consensus, high assurance levels were assigned to these pairwise comparisons.

3.3 The computation of each DM's set of E_{ki}

On the basis of Tables 3, 4, and 5, Z^{t}_{xy} and Z^{nt}_{xyk} are derived using Eqs. 1, 3, and 4 (Tables 6 and 7). The computations are performed with the programs coded in Matlab software. Two following examples are used to demonstrate the computation.

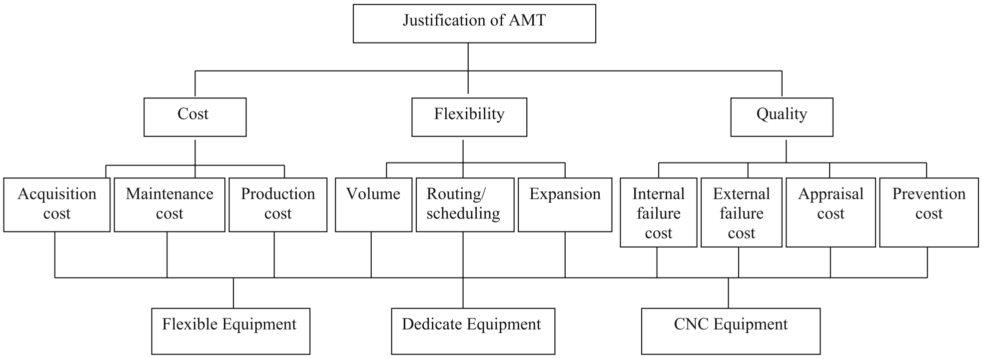


Fig. 1 Structure of the criteria used in the TJTE case

Table 3 DMs' pairwise comparisons for criteria at layers 1 and 2

		DM_1	DM_2	DM_3	DM_4
Layer 1	Cost vs. flexibility	3 (H)[a]	5 (M)	1/3 (H)	5 (H)
	Cost vs. quality	2 (H)	1 (H)	1/3 (H)	2 (H)
	Flexibility vs. quality	1/2 (H)	1/3 (H)	1 (H)	1/3 (H)
Layer 2	Acquisition vs. maintenance	3 (H)	1 (L)	1/5 (M)	5 (H)
	Acquisition vs. production	1 (H)	1/5 (L)	1/5 (M)	3 (H)
	Maintenance vs. production	1/4 (H)	1/5 (L)	1/2 (H)	2 (H)
	Volume vs. routing	1/3 (M)	5 (H)	1 (H)	1 (L)
	Volume vs. expansion	1 (M)	5 (H)	4 (H)	1/3 (L)
	Routing vs. expansion	4 (M)	1 (H)	4 (H)	1/3 (L)
	Internal vs. external	1 (M)	1/5 (H)	5 (H)	1 (M)
	Internal vs. appraisal	4 (H)	1 (M)	2 (M)	1 (H)
	Internal vs. prevention	2 (H)	1/5 (M)	1/3 (M)	1 (M)
	External vs. appraisal	3 (H)	5 (H)	2 (L)	1 (H)
	External vs. prevention	2 (H)	1 (H)	1/3 (L)	1 (M)
	Appraisal vs. prevention	1/2 (M)	1/5 (L)	1/5 (M)	1 (M)

[a] The letter in the parentheses indicates the assurance level to the corresponding pairwise comparison, where H for high, M for medium, and L for low

Acquisition cost in Table 4 is used to show the computation of Z^t_{xy} as follows.

$$Z^t_{\mathrm{FD}} = \left[1 - e^{-(2{,}000{,}000/1{,}800{,}000)/3.7}\right] \times 9 = 2.335,$$

$$Z^t_{\mathrm{DF}} = \left[1 - e^{-(1{,}800{,}000/2{,}000{,}000)/3.7}\right] \times 9 = 1.943,$$

$$Z^t_{\mathrm{FT}} = \left[1 - e^{-(300{,}000/1{,}800{,}000)/3.7}\right] \times 9 = 0.396,$$

$$Z^t_{\mathrm{TF}} = \left[1 - e^{-(1{,}800{,}000/300{,}000)/3.7}\right] \times 9 = 7.222,$$

$$Z^t_{\mathrm{DT}} = \left[1 - e^{-(300{,}000/2{,}000{,}000)/3.7}\right] \times 9 = 0.358,$$

$$Z^t_{\mathrm{DT}} = \left[1 - e^{-(2{,}000{,}000/300{,}000)/3.7}\right] \times 9 = 7.515.$$

The pairwise comparison of "Cost vs. Flexibility" from DM_1 in Table 3 is extracted to illustrate the computation of Z^{nt}_{xyk}, where the pairwise comparison is $\tilde{3}$ and the assurance level is high. According to Eq. 3,

$$Z_{\mathrm{CF1}} = Z^2_{\mathrm{CF1}}\left[0.05^2 - (0.65 - 0.6)^2\right] + \left[Z_{\mathrm{CF1}}(1 + 2 \times 0.65(0.65 - 0.6) + 2 \times 0.45 \times 0.05\right] + 0.45^2 - 0.65^2.$$

Then, Z_{CF1} is solved to be 0.198.

Subsequently, by Eq. 4,

$$Z^{nt}_{\mathrm{CF1}} = \frac{0.198 - (-0.191)}{0.763 - (-0.191)} \times 9 = 3.668$$

After deriving the set of Z^t_{xy}s and each DM's sets of Z^{nt}_{xyk}s, all DMs' E_{ki} can be obtained through the eigenvector and the hierarchical composition methods. The evaluations obtained through eigenvector method are listed in Fig. 2, and then the E_{ki} for each DM are obtained as follows:

$$\begin{aligned} E_{1i} &= \left(\begin{bmatrix} 0.174 & 0.149 & 0.345 \\ 0.158 & 0.255 & 0.339 \\ 0.669 & 0.597 & 0.316 \end{bmatrix} \times \begin{bmatrix} 0.373 \\ 0.230 \\ 0.398 \end{bmatrix}, \begin{bmatrix} 0.855 & 0.793 & 0.855 \\ 0.015 & 0.019 & 0.015 \\ 0.130 & 0.189 & 0.130 \end{bmatrix} \times \begin{bmatrix} 0.300 \\ 0.453 \\ 0.264 \end{bmatrix} \right. \\ &\quad \left. \begin{bmatrix} 0.614 & 0.512 & 0.372 & 0.180 \\ 0.221 & 0.332 & 0.372 & 0.208 \\ 0.166 & 0.156 & 0.257 & 0.613 \end{bmatrix} \times \begin{bmatrix} 0.298 \\ 0.283 \\ 0.182 \\ 0.237 \end{bmatrix} \right) \times \begin{bmatrix} 0.180 \\ 0.208 \\ 0.613 \end{bmatrix} \\ &= (0.429,\ 0.219, 0.352). \end{aligned}$$

In the same way,

$$E_{2i} = (0.399, 0.239, 0.362),$$

$$E_{3i} = (0.484, 0.201, 0.316),$$

$$E_{4i} = (0.372, 0.232, 0.396).$$

3.4 The determination of DM's weights and the aggregation of E_{ki}

As stated in Section 3.3, each DM's weight is determined on the basis of his/her assurance levels about pairwise

Table 4 Data of alternatives for criteria in cost category at Layer 3

Criteria	Alternatives		
	Flexible equipment	Dedicate equipment	CNC equipment
Acquisition cost	1,800,000	2,000,000	300,000
Maintenance cost			
Material	30,000	15,000	5,000
Time (h/month)	50	30	10
Production cost			
Direct labor	12	7.5	20
Direct material	25	25	25
Manufacture fee	6.25	11.58	2.78

comparisons. One DM's assurance levels are grouped into assurance matrices used to derive each matrix's maximum eigenvalue (λ^a_{xy}). Then, each λ^a_{xyk} is transferred to λ^{na}_{xyk} via Eqs. 5 and 6. Figure 3 shows the example for DM$_1$.

DM$_k$'s weight, w_k, is obtained by using hierarchical composition to integrate his/her related λ^{na}_{xyk}, such as

$$\begin{aligned} w_1 &= 0.260 \times [0.260 \times (0.260 + 0.260 + 0.260) \\ &\quad + 0.2 \times (0.260 + 0.260 + 0.260) \\ &\quad + 0.335 \times (0.260 + 0.260 + 0.260)] \\ &= 0.317 \end{aligned}$$

The weights of other DMs are obtained in the same way and are listed as follows:

$$w_2 = 0.194, w_3 = 0.271, w_4 = 0.219.$$

Finally, each alternative's priority, E_i, is acquired via WGMM as follows:

$$\begin{aligned} E_1 &= (0.429)^{0.317} \times (0.399)^{0.194} \times (0.484)^{0.271} \times (0.372)^{0.219} = 3.229. \\ E_2 &= (0.219)^{0.317} \times (0.239)^{0.194} \times (0.201)^{0.271} \times (0.232)^{0.219} = 2.750. \\ E_3 &= (0.352)^{0.317} \times (0.362)^{0.194} \times (0.316)^{0.271} \times (0.396)^{0.219} = 3.088. \end{aligned}$$

Since the priority of flexible equipment was obviously higher than those of other alternatives, the decision-making team recommended flexible equipment for future production.

4 Conclusions

Two requisites of a robust AMT justification model are deduced from available literature, including the hybrid process and the group decision. This study extends Saaty's AHP to fuzzy theory and group decision environment for justifying AMT and is verified through the application to a Taiwanese case. The proposed models possess the following features.

1. AHP is extended to handle both tangible and intangible criteria by maintaining the pairwise comparisons for conforming to the requisite about a hybrid process.
2. The linguistic pairwise comparison is transformed to fuzzy number, instead of crisp value, to improve the unbalanced scale issue during Saaty's AHP.
3. Assurance level is introduced into the transformation of the fuzzy number to its representative value. With the assurance level, which indicates a DM's confidence for his/her judgment, more information about DMs' judgments are included in decision process and ambiguity is eliminated.
4. A novel approach to derive the weights of DMs in group decisions aggregation is proposed, in which assurance level is regarded as essential to determining weights of DMs.

Table 5 Pairwise comparisons among alternatives for criteria at layer 3 except for the criteria in cost category

Criteria	Flexible vs. dedicated	Flexible vs. CNC	Dedicate vs. CNC
Volume flexibility	9	7	1/7
Routing flexibility	9	6	1/7
Expansion flexibility	9	7	1/7
Internal failure cost	6	6	3
External failure cost	3	7	3
Appraisal cost	1	3	3
Prevention cost	1/2	1/2	1/6

Table 6 The Z^{nt}_{xyk} of the pairwise comparisons at layers 1 and 2

Layer	Comparison	DM_1		DM_2		DM_3		DM_4	
		Z^{nt}_{xy1}	Z^{nt}_{yx1}	Z^{nt}_{xy2}	Z^{nt}_{yx2}	Z^{nt}_{xy3}	Z^{nt}_{yx3}	Z^{nt}_{xy4}	Z^{nt}_{yx4}
1	Cost vs. flexibility	3.668	1.798	4.801	0.511	1.798	3.668	5.468	0.810
	Cost vs. quality	3.143	2.207	2.656	2.656	1.798	3.668	3.143	2.207
	Flexibility vs. quality	2.207	3.143	1.798	3.668	2.656	2.656	1.798	3.668
2	Acquisition vs. maintenance	3.668	1.798	2.422	2.422	0.511	4.801	5.468	0.810
	Acquisition vs. production	2.656	2.656	0.725	3.779	0.511	4.801	3.668	1.798
	Maintenance vs. production	1.258	4.527	0.725	3.779	2.207	3.143	3.143	2.207
	Volume vs. routing	1.798	3.514	5.468	0.810	2.656	2.656	2.422	2.422
	Volume vs. expansion	2.656	2.656	5.468	0.810	4.527	1.258	1.798	2.994
	Routing vs. expansion	4.157	1.154	2.656	2.656	4.527	1.258	1.798	2.994
	Internal vs. external	2.656	2.656	0.810	5.468	5.468	0.810	2.656	2.656
	Internal vs. appraisal	4.527	1.258	2.656	2.656	3.085	2.227	2.656	2.656
	Internal vs. prevention	3.143	2.207	0.511	4.801	1.798	3.514	2.656	2.656
	External vs. appraisal	3.668	1.798	5.468	0.810	2.713	2.117	2.656	2.656
	External vs. prevention	3.143	2.207	2.656	2.656	1.798	2.994	2.656	2.656
	Appraisal vs. prevention	2.223	3.085	0.725	3.779	0.511	4.801	2.656	2.656

Table 7 The Z^{t}_{xy} of pairwise comparisons among alternatives at layer 3

Criteria	Comparison on alternatives	Z^{t}_{xy}	Z^{t}_{yx}
Acquisition cost	Flexible vs. dedicated	2.335	1.943
	Flexible vs. CNC	0.396	7.222
	Dedicated vs. CNC	0.358	7.515
Maintenance cost	Flexible vs. Dedicated	1.242	3.511
	Flexible vs. CNC	0.435	6.946
	Dedicated vs. CNC	0.775	5.000
Production cost	Flexible vs. Dedicated	2.167	2.096
	Flexible vs. CNC	2.323	1.953
	Dedicated vs. CNC	2.286	1.986
Volume flexibility	Flexible vs. Dedicated	9.000	0
	Flexible vs. CNC	7.593	0.195
	Dedicated vs. CNC	0.195	7.593
Routing flexibility	Flexible vs. dedicated	9.000	0
	Flexible vs. CNC	6.490	0.455
	Dedicated vs. CNC	0.195	7.593
Expansion flexibility	Flexible vs. Dedicated	9.000	0
	Flexible vs. CNC	7.593	0.195
	Dedicated vs. CNC	0.195	7.593
Internal failure cost	Flexible vs. Dedicated	6.490	0.455
	Flexible vs. CNC	6.490	0.455
	Dedicated vs. CNC	3.668	1.798
External failure cost	Flexible vs. dedicated	3.668	1.798
	Flexible vs. CNC	7.593	0.195
	Dedicated vs. CNC	3.668	1.798
Appraisal cost	Flexible vs. Dedicated	2.656	2.656
	Flexible vs. CNC	3.668	1.798
	Dedicated vs. CNC	3.668	1.798
Prevention cost	Flexible vs. dedicated	2.207	3.143
	Flexible vs. CNC	0.455	6.490
	Dedicated vs. CNC	0.455	6.490

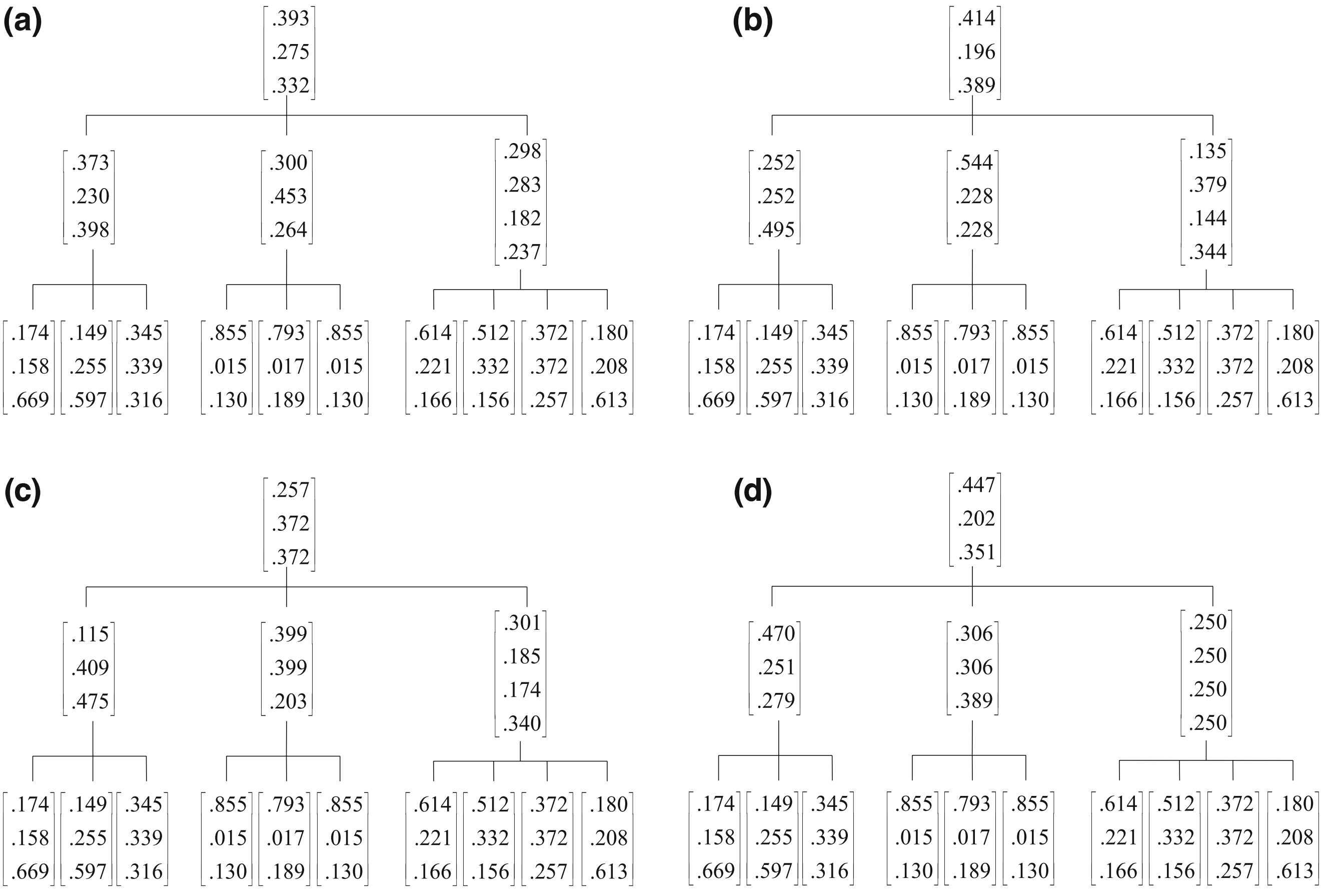
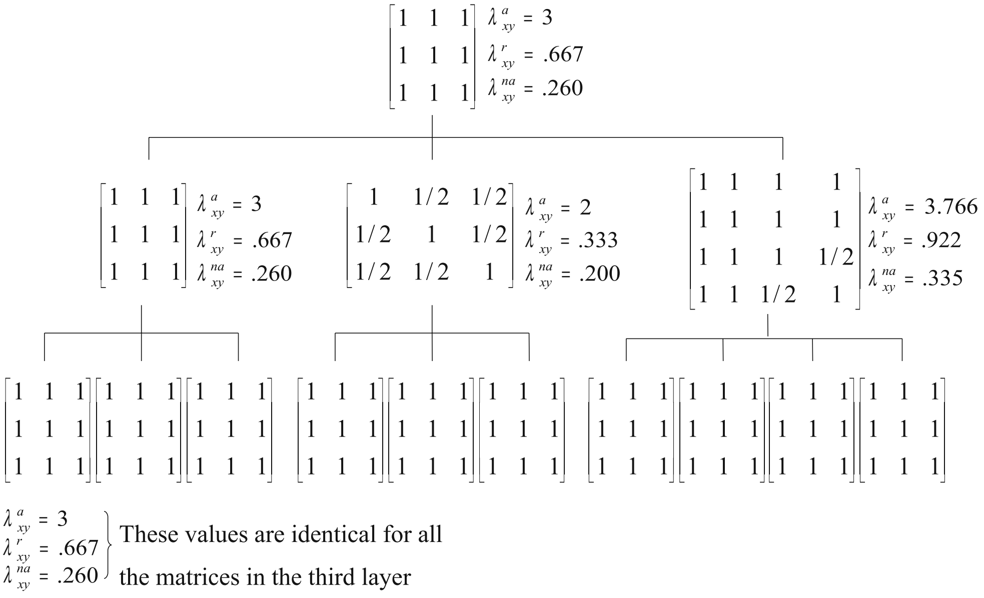


Fig. 2 Priorities for criteria/alternatives through the maximum eigenvector method (a) DM_1 (b) DM_2 (c) DM_3 (d) DM_4

Fig. 3 DM_1's assurance matrices and the corresponding λ_{xy}^{a}, λ_{xy}^{r}, and λ_{xy}^{na}



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